Alternate Fuels: Thorium and Uranium-233

Report to Congress
March 2023

United States Department of Energy
Washington, DC 20585

Message from the Secretary

This report addresses a requirement in section 2001(b)(3) of the Energy Act of 2020 as well as a request in the House Report accompanying the Energy and Water Development and Related Agencies Appropriations Bill, 2022 for the Department of Energy ("the Department" or DOE) to report on the use of thorium and uranium-233 (U-233) U-233 as fuel for advanced nuclear reactor research, development, demonstration, or commercial application purposes. The Energy Act of 2020 directs the Department to provide a report describing the potential use of thorium fuel and U-233 in future Generation IV reactor designs, and in current operating light water reactors (LWRs). In 2022, the Department received a congressional request to provide a report describing whether it is working with other nations to develop thorium molten-salt reactors (TMSRs). In addition, Congress requested the Department to provide suggestions and considerations for Congress regarding the development of a domestic TMSR program. This report address both the statutory requirement and the House Appropriations request.

The direction in the Energy Act of 2020 Sec. 2001(b)(3) states:

"Not later than 180 days after the date of enactment of this Act, the Secretary shall, after consulting with relevant entities, including National Laboratories, institutions of higher education, and technology developers, submit to Congress a report identifying any and all options for providing nuclear material, containing isotopes other than the uranium-235 isotope, such as uranium-233 and thorium-232 to be used as fuel for advanced nuclear reactor research, development, demonstration, or commercial application purposes."

The 2020 House Appropriations Report (H.Rep. 117-98) accompanying the Energy and Water Development and Related Agencies Appropriations Bill, 2022 requested the Department:

"[n]ot later than 90 days after enactment of this Act [to provide] a report indicating whether the Department is working with any other nations to develop TMSR programs. The report should also include suggestions and considerations for Congress regarding the development of a domestic TMSR program, including the potential benefits and challenges of the technology, necessary infrastructure investments, fuel cycle considerations, proliferation issues, and the potential for using the federal U–233 supply and any resulting impacts to cleanup milestones or costs of cleanup or security activities related to the supply.[1]

This report is being provided to the following Members of Congress:

- **The Honorable Patty Murray**
  Chair, Senate Committee on Appropriations

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[1] House Report 117-98, "Energy and Water Development and Related Agencies Appropriations Bill, 2022," Accompanies H.R. 4549, House Appropriations Committee, submitted by M. Kaptur.

- **The Honorable Susan Collins**
  Vice Chair, Senate Committee on Appropriations

- **The Honorable Dianne Feinstein**
  Chair, Subcommittee on Energy and Water Development
  Senate Committee on Appropriations

- **The Honorable John Kennedy**
  Ranking Member, Subcommittee on Energy and Water Development
  Senate Committee on Appropriations

- **The Honorable Kay Granger**
  Chairwoman, House Committee on Appropriations

- **The Honorable Rosa DeLauro**
  Ranking Member, House Committee on Appropriations

- **The Honorable Chuck Fleischmann**
  Chairman, Subcommittee on Energy and Water Development
  House Committee on Appropriations

- **The Honorable Marcy Kaptur**
  Ranking Member, Subcommittee on Energy and Water Development
  House Committee on Appropriations

- **The Honorable Joe Manchin**
  Chairman, Committee on Energy and Natural Resources

- **The Honorable John Barrasso**
  Ranking Member, Committee on Energy and Natural Resources

- **The Honorable Cathy McMorris Rodgers**
  Chair, Committee on Energy and Commerce

- **The Honorable Frank Pallone, Jr.**
  Ranking Member, Committee on Energy and Commerce

- **The Honorable Frank Lucas, Jr.**
  Chairman, Committee on Science, Space, and Technology

- **The Honorable Zoe Lofgren**
  Ranking Member, Committee on Science, Space, and Technology

If you have any questions or need additional information, please contact Ms. Katie Donley, Director, Office of Budget, Office of the Chief Financial Officer, at (202) 586-0176; Ms. Becca Ward, Deputy Assistant Secretary for Senate Affairs or Ms. Janie Thompson, Deputy Assistant Secretary for House Affairs, Office of Congressional and Intergovernmental Affairs, at (202) 586-5450.

Sincerely,

Jennifer Granholm

Executive Summary

This report describes the potential use of thorium fuel and uranium-233 (U-233) in future Generation IV reactor designs and in current light water reactors. Various thorium fuel cycle options using fertile thorium along with fissile uranium fuel could serve to increase fuel burnup, extend fuel resources, reduce the need for uranium enrichment facilities and uranium mining, and significantly lower spent fuel volume and waste radiotoxicity over time. This report describes the potential benefits, disadvantages, and economics of using thorium and U-233 to fuel nuclear reactors as well as the use of thorium for non-nuclear applications.

The direction in the Energy Act of 2020 section 2001(b)(3) states:

"Not later than 180 days after the date of enactment of this Act, the Secretary shall, after consulting with relevant entities, including National Laboratories, institutions of higher education, and technology developers, submit to Congress a report identifying any and all options for providing nuclear material, containing isotopes other than the uranium-235 isotope, such as uranium-233 and thorium-232 to be used as fuel for advanced nuclear reactor research, development, demonstration, or commercial application purposes."

The Department also received a congressional request in 2022 to provide a report describing whether it is working with other nations to develop TMSRs. Congress also requested the Department to include, suggestions and considerations for Congress regarding the development of a domestic TMSR program in this report. Specifically, the House Energy and Water Development and Related Agencies Appropriations, House Report 117-98, accompanying the Energy and Water Development and Related Agencies Appropriations Bill, 2022 requested the Department to provide:

"[n]ot later than 90 days after enactment of this Act a report indicating whether the Department is working with any other nations to develop TMSR programs. The report should also include suggestions and considerations for Congress regarding the development of a domestic TMSR program, including the potential benefits and challenges of the technology, necessary infrastructure investments, fuel cycle considerations, proliferation issues, and the potential for using the federal U–233 supply and any resulting impacts to cleanup milestones or costs of cleanup or security activities related to the supply."[2]

This report focuses on the use of thorium-232 (Th-232) and U-233 since other nuclear reactor isotopes such as uranium-235 (U-235) and uranium-238 (U-238) and those isotopes derived from spent nuclear fuel (plutonium, neptunium, americium, and curium) are well understood as fuel for nuclear reactor applications. This report describes thorium fuel cycles and the development of a domestic TMSR program, including the potential benefits and challenges of

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[2] House Report 117-98, "Energy and Water Development and Related Agencies Appropriations Bill, 2022," Accompanies H.R. 4549, House Appropriations Committee, submitted by M. Kaptur.

thorium reactor technology, needed infrastructure investments, fuel cycle considerations, and proliferation issues.

The history of United States (U.S.) and foreign thorium-fueled reactor research, development, and reactor deployments is summarized in this report. Current U.S. and international thorium fuel cycle and technology research activities and development programs are described, and countries interested in advanced thorium reactors are highlighted. While the U.S. monitors thorium-fueled reactor research, development, and deployments internationally, the U.S. is not currently working with any other nations to develop TMSR programs.

Future U.S. thorium fuel utilization would have to overcome several challenges since no thorium infrastructure exists in the United States. Building the complete infrastructure that would be needed in the U.S. for deploying thorium fueled reactors would cost much more than continuing to use uranium fuel. Significant gamma shielding and remote handling would be required for any irradiated thorium fuel storage or potential reprocessing. In the case of similar thorium fuel cycle technologies being deployed overseas, including especially in non-nuclear weapon states, new and improved safeguards and security methodologies and technologies would need to be further developed for thorium fuel cycles that create fissile U-233, which is a serious nuclear weapons proliferation issue. Thorium fuel would have to be “denatured” with natural or depleted uranium to mitigate the proliferation problem caused by thorium irradiation producing not only fissile U-233 but also protactinium isotopes that decay into pure U-233.

U.S. thorium demand for nuclear and non-nuclear applications could be aided by removing thorium from monazite mining waste (i.e., “tails”) to allow for rare earth elements (REEs) extraction. Thorium is nearly always bound to REE minerals in waste residual inventories as byproducts of phosphate, iron, coal, and titanium mining activities. Phosphate monazite “tails” have very high concentrations of key REEs, thorium and uranium, enough for current U.S. and international REEs demand and future thorium fuel needs. Separating naturally radioactive thorium from monazite mining wastes would allow for the safe extraction of REEs from existing phosphate monazite wastes ponds and eliminate the need to ever directly mine thorium. The removed thorium could be stored in thorium “bank” facilities for fueling future thorium-fueled nuclear reactors and for non-nuclear applications. Several existing U.S. monazite waste sites could be remediated by removing thorium so that REEs can be extracted to meet current U.S. needs and supply some of the world-wide REE demand.

However, because of the challenges for thorium-fueled reactors, the Office of Nuclear Energy continues to focus on uranium-based reactors and does not plan to initiate a separate ongoing thorium reactor program.

Alternate Fuels: Thorium and Uranium-233

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Acronyms

AHWR	Advanced Heavy Water Reactor
ANL	Argonne National Laboratory
ATR	Advanced Test Reactor
BARC	Bhabha Atomic Research Centre
BNL	Brookhaven National Laboratory
BWR	Boiling Water Reactor
CANDU	Canadian Deuterium Uranium
CAS	Chinese Academy of Sciences
CRADA	Cooperative Research and Development Agreement
DMSR	Denatured Molten Salt Reactor
DOE	Department of Energy (the Department)
EAR	Estimated Additional Reserves
EM	Office of Environmental Management
FBTR	Fast Breeder Test Reactor
GAIN	Gateway for Accelerated Innovation in Nuclear
HEU	Highly Enriched Uranium
HWR	Heavy Water Reactor
HTGR	High Temperature Gas-cooled Reactor
HTR	High Temperature Reactor
I^2S-LWR	Integral Inherently Safe Light Water Reactor
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
INL	Idaho National Laboratory
LFTR	Liquid Fluoride Thorium Reactor
LWR	Light Water Reactor
MC&A	Material Control and Accountability
MOU	Memorandum of Understanding
MOX	Mixed Oxide
MSBR	Molten Salt Breeder Reactor
MSR	Molten Salt Reactor
NRC	U.S. Nuclear Regulatory Commission
NE	Office of Nuclear Energy
NEA	Nuclear Energy Agency
NERI	Nuclear Energy Research Initiative
NEST	Nuclear Energy Sciences and Technologies
NEUP	Nuclear Energy University Program
ORNL	Oak Ridge National Laboratory
PAR	Parabolic Aluminized Reflector
PHWR	Pressurized Heavy Water Reactor
PNNL	Pacific Northwest National Laboratory

PWR	Pressurized Water Reactor
RAR	Reasonably Assured Reserves
REE	Rare Earth Element
R&D	Research and Development
SINAP	Shanghai Institute of Applied Physics
THTR	Thorium High Temperature Reactor
THOREX	Thorium uranium extraction
TIG	Tungsten Inert Gas (welding)
TMSR	Thorium Molten Salt Reactor (Th-MSR)
TRISO	Tri-structural isotropic
UOX	Uranium Oxide
USGS	U.S. Geological Survey
UV	Ultraviolet
ZPR	Zero Power Reactor

I. Legislative Language

The Energy Act of 2020 Sec. 2001(b)(3) directs the Department of Energy**:**

"Not later than 180 days after the date of enactment of this Act, the Secretary shall, after consulting with relevant entities, including National Laboratories, institutions of higher education, and technology developers, submit to Congress a report identifying any and all options for providing nuclear material, containing isotopes other than the uranium-235 isotope, such as uranium-233 and thorium-232 to be used as fuel for advanced nuclear reactor research, development, demonstration, or commercial application purposes."

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II. Introduction

This report focuses on the use of thorium-232 (Th-232) and U-233 since other nuclear reactor isotopes such as uranium-235 (U-235) and uranium-238 (U-238) and those isotopes derived from spent nuclear fuel (plutonium, neptunium, americium, and curium) are well understood as fuel for nuclear reactor applications. Options for providing unirradiated Th-232 fuel for new reactors, issues regarding the thorium fuel cycle, handling irradiated thorium fuel and the resultant radioactive isotope U-233 proliferation risks will be discussed in terms of benefits and challenges. This report also describes several non-nuclear commercial applications for Th-232 and the various medical isotopes that could be produced. The opportunity of extracting needed essential rare earth minerals for other commercial applications from existing monazite mining wastes that contain radioactive Th-232 is discussed. Th-232 for future concepts and valuable rare earth minerals could be obtained without opening new mines or depending on foreign suppliers, such as the People's Republic of China.

Thorium is a radioactive chemical element with atomic number 90 and has an atomic weight of 232.0377 in nature. All known thorium isotopes are unstable. The most stable isotope, Th-232, has a half-life of 14.05 billion years, and it decays very slowly via alpha (2n, 2p) decay first to

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[3] House Report 117-98, "Energy and Water Development and Related Agencies Appropriations Bill, 2022," Accompanies H.R. 4549, House Appropriations Committee, submitted by M. Kaptur.

Radium (Ra-228) in a long decay chain that ends with the stable lead isotope Pb-208. On Earth, thorium and uranium are the only significantly radioactive elements that still occur naturally in large quantities as primordial elements. Appendix A describes the neutronic capture and transmutation and decay chains associated with thorium, uranium, and the decay isotopes in detail.

Thorium has potential to become a valuable energy source. It is three to four times as abundant as uranium and is more widely distributed in the earth's crust than uranium. Historical concerns over the availability of uranium reserves and the greater geographic distribution of thorium pointed to thorium as a potential nuclear fuel candidate. Thorium fuel was studied during the 1960s - 1980s in the United States and other countries as a potential basis for nuclear fuel cycles. After some demonstration of feasible thorium fuel cycle concepts, the U.S. decided instead to use uranium-fueled LWRs and liquid metal-cooled fast reactors using uranium and plutonium. U.S. and global uranium sources were determined to be more than sufficient for the current world reactor needs.[4,5] Worldwide interest in thorium fuel cycle development continued at a reduced level, with India deploying the most thorium-fueled reactors.

Recently interest in thorium-based fuel cycles has returned because of the possibility of worldwide nuclear energy growth using advanced reactor designs that enhance safety, proliferation resistance, and economics. Countries with low uranium reserves but large indigenous thorium deposits could deploy thorium-fueled reactors to meet their power needs and reduce their carbon emissions with less reliance on foreign sources of nuclear feedstock.

This report discusses historical experience with the thorium/U-233 fuel cycle, describes its inherent attributes, identifies issues that must be resolved, provides information about new thorium reactor concepts, and addresses proliferation concerns. Appendix A provides details about thorium physics in terms of decay chains, neutron capture, and physical attributes. Appendix B discusses U.S. and worldwide thorium resources.

Detailed technical reports from DOE National Laboratories, technical journal articles, valuable information from thorium fuel cycle advocates and public thorium websites, trade magazines, and various agencies including the U.S. Geological Survey (USGS), U.S. Nuclear Regulatory Commission (NRC), International Atomic Energy Agency (IAEA), Nuclear Energy Agency (NEA), and many other references found through a thorough literature search were used to provide accurate information about thorium and U-233 fuel utilization, and are cited in the References section.

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[4] U.S. Geological Survey, Thorium Statistics and Information: Mineral commodity summaries, published annually, U.S. Geological Survey, Reston, VA. Available at: https://www.usgs.gov/centers/nmic/thorium-statistics-and-information#mcs.

[5] World Nuclear Association, "Thorium," World-nuclear.org, November 2020. Available at: https://www.world-nuclear.org/information-library/current-and-future-generation/thorium.aspx#References.

III. Historical U.S. and International Thorium Fueled Reactor Programs

Thorium, discovered in 1828, was first used in 1885 when Carl von Welsbach invented the gas mantle as a portable source of incandescent light when heated by burning gases. Thorium's radioactivity was discovered in 1898 by Gerhard Carl Schmidt and later that year, independently, by Marie Curie. By 1950, thorium was replaced in many non-nuclear uses because of concerns about its radioactivity. Thorium fuel utilization has been demonstrated in LWRs, as well as in other reactor types including fast spectrum reactors, molten salt reactors (MSRs), heavy water reactors (HWRs), and high temperature gas-cooled reactors (HTGRs). Thorium fuels have been proven to be a viable alternative to uranium fuel cycles and have been used in several test reactors and full-scale power reactor cores in HTGRs, MSRs, and boiling and pressurized LWRs in five countries. Table 3.1 provides details about experimental and power thorium fueled reactors around the world.

U.S. Thorium-fueled Reactors

Thorium was used successfully in the U.S in several experimental research reactors, demonstration reactors, and large power reactors from the mid-1950s until the mid-1980s using fuel elements (Th, U)O_2 and (Th, U)C2 fuels in HTGRs, (Th, U)O_2 fuel in LWRs and HWRs, and as circulating fuel in FLiBe molten salt ($Li_7F/BeF_2/ThF_4/UF_4$) in molten salt breeder reactors (MSBRs).

Some of the first U.S. commercial LWRs developed in the late 1950s and early 1960s were initially operated with thorium-based fuels. The earliest U.S. thorium-based pressurized LWR was the **Indian Point Unit 1** located in Buchanan, New York beginning in September 1962 with its first core using enriched U-235 and thorium fuel with stainless steel cladding. Subsequent Indian Point 1 core loadings operated without thorium fuel and used only uranium dioxide fuel until Indian Point 1 was shut down in 1974.[6,7]

The small 22 MW **Elk River** Boiling Water Reactor (BWR) in Minnesota operated from July 1964 until February 1968. The **BORAX IV** test reactor in Idaho was a BWR which used thorium/uranium plates that were manufactured with intentional defects to see how thorium fuel would perform in a boiling water environment. Both Elk River and Borax IV used high density (Th, U)O_2 fuel pellets containing 4–7 percent UO_2 in rodlets.

The **Peach Bottom Unit 1** plant in Pennsylvania was a demonstration HTGR with mixed thorium and uranium coated particle fuel compacts that operated from 1967-1972. It used thorium-

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[6] Nuclear Energy Agency, "Introduction of Thorium in the Nuclear Fuel Cycle: Short- to long-term considerations, OECD NEA No. 7224, 2015.

[7] IAEA Report 1450: International Atomic Energy Agency, Sokolov, F., K. Fukuda, and H. P. Nawada, "Thorium Fuel Cycle—Potential Benefits and Challenges," IAEA-TECDOC-1450, Vienna, May 2005.

highly enriched uranium (HEU) carbide kernels that had two coating layers bi-structural isotropic or buffer isotropic (BISO) particle fuel with mixed thorium-uranium carbide kernels coated with a silicon carbide layer to retain fission products and a single pyrolytic carbon layer that were embedded in annular graphite segments. Peach Bottom 1 produced 33 billion kWh over 1349 equivalent full-power days with a capacity factor of 74 percent.

The **Fort Saint Vrain High Temperature Reactor (HTR)** in Colorado was a larger-scale commercial successor to the Peach Bottom 1 reactor and operated between 1976-1989. It used thorium-HEU fuel in the form of tri-structural isotropic (TRISO) particle fuel or microspheres of mixed thorium-uranium carbide kernels coated with a single silicon oxide layer and two inner and outer pyrolytic carbon layers to retain fission products. The TRISO particles were embedded in graphite compacts that were arranged in hexagonal prismatic graphite blocks. Almost 25 tons of thorium fuel was used in the reactor and much of the fuel attained a very high burnup of about 170 GWd/t.

The **Shippingport reactor** in Pennsylvania was the world's first full-scale nuclear electric power plant and went "critical" in December 1957 and ran until October 1982 and had three distinct core configurations.[8] The first core used 93 percent enriched uranium as "seed" fuel surrounded by a "blanket" of natural U-238 where about half the power came from the seed. The second core was similarly designed but with a different design in the seed region.

The third Shippingport core was an experimental, light water moderated, thermal thorium breeder reactor and operated from August 1977 until 1982. This core design demonstrated that the Radkowsky seed-and-blanket core design concept could work well in a pressurized LWR.[9] The third core's seed region used fissile U-233 oxide and the blanket had fertile thorium dioxide fuel. Initially the U-233 content of the seed pellets was 5-6 percent and 1.5-3 percent in the blanket region. As a breeder reactor, it transmuted inexpensive, unenriched thorium into U-233 as part of its fuel cycle. Post-irradiation evaluations of Shippingport's spent fuel pins showed that 1.39 percent more fissile fuel was present compared with the initial fuel inventory proving that thermal energy breeding had indeed occurred in the fuel;[10] whereas a NRC 2007 report quotes a breeding ratio of 1.01. Over its 25-year life, the Shippingport power plant operated for about 80,324 hours, producing about 7.4 billion kilowatt-hours of electricity.

The **Molten Salt Thorium Research Reactor** at Oak Ridge National Laboratory (ORNL) in Tennessee was a demonstration MSR that used fissile thorium and produced U-233 as the main fissile driver in its second campaign. ORNL's research also produced MSBR designs that would have peak operating temperatures of 705 °C, and the thorium designs were calculated to have

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[8] Banerjee, S.; Gupta, H. P.; Bhardwaj, S. A., "Nuclear power from thorium: different options," Current Science. Vol. 111, No. 10, November 25, 2016, pp, 1607–1623.

[9] Radkowsky, Alvin, Alex Galperin, "The Nonproliferative Light Water Thorium Reactor: A New Approach to Light Water Reactor Core Technology," Nuclear Technology, Vol 124, December 1998, pp. 215-222.

[10] Banerjee, S.; Gupta, H. P.; Bhardwaj, S. A., "Nuclear power from thorium: different options," Current Science. Vol. 111, No. 10, November 25, 2016, pp, 1607–1623.

a breeding ratio of 1.04. The MSR research and development (R&D) at ORNL was cancelled in preference to the sodium-cooled fast breeder reactor program.

In 1973 the United States effectively discontinued thorium-related nuclear research because uranium-fueled reactors were a proven, efficient technology and thorium's breeding ratio in LWRs was considered to be too low to produce enough fuel to support development of a commercial nuclear industry. For most countries, including the United States, uranium is relatively abundant so that the deployment of thorium-based power reactors has been limited. Table 3.1 shows the different thorium-fueled reactors that have been deployed worldwide.[11] Table 3.2 compares the types of fuel cycles used in LWRs, HWRs, HTGRs, and MSRs.[12]

International Thorium-fueled Reactors

The IAEA began several thorium reactor studies in 1996.[13,14] Between 1999 and 2021, the number of operational thorium reactors in the world went from zero, to a handful of research reactors, to commercial plans for producing full-scale thorium-based reactors for use as plants on a national scale. Various types of reactors have used and can use different forms of thorium fuel.[15] Table 3.2 compares the types of fuel cycles used in LWRs, HWRs, HTGRs, and MSRs. The history of thorium reactor research, development, and deployment, as well as the current status of thorium reactor activities around the world is described next by country, alphabetically.

Canada

Although natural uranium is used in Canadian Deuterium Uranium (CANDU) reactors, they are capable of using thorium. In 2012, Canada started to work with China on the thorium fueled Advanced Fuel CANDU Reactor, which is a further evolution of Canada's CANDU6 design.[16] In 2013, Thorium Power Canada proposed to develop a thorium powered 10 MW demonstration reactor that would be used to power a desalination plant in Chile, and a 25 MW power plant for

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[11] Sokolov, F., K. Fukuda, H. P. Nawada, "Thorium Fuel Cycle—Potential Benefits and Challenges," IAEA-TECDOC-1450, International Atomic Energy Agency (2005).

[12] Worrall, Louise G., A Worrall, G. F. Flanagan, et al., "Safeguards Considerations for Thorium Fuel Cycles," Nuclear Technology, Vol 194, No. 2, May 2016, pp. 281-293.

[13] Majumdar, S.,D. Purushotham, "Experience of thorium fuel development in India," in IAEA-TECDOC-1319, "Thorium fuel utilization: Options and trends Proceedings of three IAEA meetings held in Vienna in 1997, 1998 and 1999," International Atomic Energy Agency (1999), pp. 69-76.

[14] Sokolov, F., K. Fukuda, H. P. Nawada, "Thorium Fuel Cycle—Potential Benefits and Challenges," IAEA-TECDOC-1450, International Atomic Energy Agency (2005).

[15] World Nuclear Association, "Thorium," World-nuclear.org, November 2020. Available at: https://www.world-nuclear.org/information-library/current-and-future-generation/thorium.aspx#References.

[16] Xie, Z., P. Boczar, "CANDU Fuel-Cycle Vision," Proc. 19th Pacific Basin Nuclear Conf. (PBNC 2014), Vancouver, British Columbia, Canada, August 24–28, 2014.

Indonesia.[17] New Brunswick Energy Solutions announced a joint research program with Moltex Energy to develop the small modular Stable Salt Reactor for deployment at the Point Lepreau reactor site.[18]

China

In 2011, China announced it was initiating R&D in thorium MSR technology, claiming that they would have the world's largest national effort, and hoping to obtain full intellectual property rights on MSR technology.[19] China has recently announced in August 2022 that it should be ready to perform start-up tests for their prototype MSR.[20,21]

China anticipates that they will have their first commercial MSR completed by 2030 in the remote Gansu Province.[22] China launched their MSR program in 2011 by investing about 3 billion yuan (U.S.$500 million), according to International Thorium Molten Salt Forum located in Oiso, Japan, which has been working closely with Chinese researchers.[23] The Chinese plan to have an underground research reactor and waste storage site in Gansu near the site where they are building 120 nuclear weapons silos.[24] China has indicated that they will use thorium fuel and TMSR technology for military and strategic uses such as warships and flying drones.[25]

The Chinese thorium fuel R&D program focuses on a thorium-breeding MSR. The TMSR Research Centre has a 5 MWe MSR prototype under construction at Shanghai Institute of

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[17] Wang, Brian, "Thorium Power Canada is in advanced talks with Chile and Indonesia for 10 MW and 25 MW solid thorium fueled reactors," Next Big Future, July 2013. Available at: https://www.nextbigfuture.com/2013/07/thorium-power-canada-is-in-advanced.html

[18] Moltex, "UK Moltex seeks to deploy its Stable Salt Reactor in Canada," Nuclear Engineering International, July 18, 2018. Available at: https://www.neimagazine.com/news/newsuk-moltex-seeks-to-deploy-its-stable-salt-reactor-in-canada-6254922.

[19] Martin, Richard, "China Takes Lead in Race for Clean Nuclear Power," Wired, Feb. 1, 2011. Available at: https://www.wired.com/2011/02/china-thorium-power/

[20] Seibt, Sébastian, "Why China is developing a game-changing thorium-fuelled nuclear reactor," Dec. 9, 2021, France24.com, available at: https://www.france24.com/en/asia-pacific/20210912-why-china-is-developing-a-game-changing-thorium-fuelled-nuclear-reactor

[21] "Chinese molten-salt reactor cleared for start up," New Nuclear section, World Nuclear News, August 9, 2022, available at: https://www.world-nuclear-news.org/Articles/Chinese-molten-salt-reactor-cleared-for-start-up

[22] Patel, Prachi, "China Says It's Closing in on Thorium Nuclear Reactor: With prototype reportedly firing up in September, country teases commercial thorium power by 2030, IEEE Spectrum, August 4, 2021. Available at: https://spectrum.ieee.org/china-closing-in-on-thorium-nuclear-reactor.

[23] Mallapaty, Smriti, "China prepares to test thorium-fuelled nuclear reactor," Nature, September 13, 2021, ISSN 0028-0836 (print). Available at: https://www.nature.com/articles/d41586-021-02459-w.

[24] Lendon, Brad, Nectar Gan, "China appears to be expanding its nuclear capabilities, U.S. researchers say in new report," CNN World, July 28, 2021. Available at: https://www.cnn.com/2021/07/28/china/china-second-missile-silo-field-intl-hnk-ml/index.html.

[25] Wang, Brian, "China spending U.S. $3.3 billion on molten salt nuclear reactors for faster aircraft carriers and in flying drones," NextBigFuture.com, December 6, 2017. Available at:https://www.nextbigfuture.com/2017/12/china-spending-us3-3-billion-on-molten-salt-nuclear-reactors-for-faster-aircraft-carriers-and-in-flying-drones.html.

Applied Physics (SINAP). SINAP has two streams of MSR development: (1) TMSR-SF (solid fuel using TRISO in pebbles or prisms/blocks) in a once-through fuel cycle, and (2) TMSR-LF (liquid fuel) thorium dissolved in FLiBe molten salt coolant with reprocessing and recycle.[26] SINAP is constructing a 2 MW TMSR-SF pilot plant initially, and a 100 MW demonstration pebble bed plant with open fuel cycle by about 2030. The TMSR-LF will use a closed Th-U fuel cycle to breed U-233. SINAP aims to deploy a 10 MW TMSR-LF pilot plant by 2030 and a 100 MW demonstration plant by 2040. Currently two MSRs reactors are under construction in the Gobi Desert with completion expected in 2025. China expects to put thorium reactors into commercial and military use.[27]

Historically China worked with ORNL on uranium-fueled molten salt coolant technology under a Cooperative Research and Development Agreement (CRADA),[28] but this CRADA did not include any research for thorium-fueled MSR technology. DOE laboratory research agreements with Chinese agencies have been very limited in scope and restricted appropriately so that the U.S. nuclear fuel industry is not impacted adversely. U.S. laboratory collaborations with China are carefully monitored to protect U.S. interests and assets. It is important to note that DOE Laboratories may engage with sponsors using CRADAs which are subject to the requirements in DOE Order 483.1B for DOE review and approval.

DOE established the Nuclear Energy Sciences and Technologies (NEST) Memorandum of Understanding (MOU) Agreement with the Chinese Academy of Sciences (CAS) in December 2011.[29] Two areas were identified in the CAS NEST 2011 MOU agreement: (1) nuclear energy for non-electric applications, including materials and chemistry of molten salt coolant systems, and (2) nuclear fuel resources, with a focus on direct extraction of dissolved uranium from seawater. Under the agreed upon cooperative areas, three working groups were established: (a) Molten Salt Coolant Systems Working Group, (b) Nuclear Fuel Resources Working Group, and (c) Nuclear Hybrid Energy Systems Working Group. The DOE-CAS MOU[30] focused on uranium (no thorium) and using molten salt as coolant with solid fuel, versus fuel-flowing-in-the-molten salt. The US DOE has not collaborated with China on thorium fuel technologies.

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[26] Sun, L., et al., “Conceptual Design and Analysis of a Passive Residual Heat Removal System for a 10 MW Molten Salt Reactor Experiment,” Prog. Nuclear Energy, vol. 70, number 149, 2014.

[27] Wang, Brian, “China spending U.S. $3.3 billion on molten salt nuclear reactors for faster aircraft carriers and in flying drones,” Next Big Future, December 2017. Available at: https://www.nextbigfuture.com/2017/12/china-spending-us3-3-billion-on-molten-salt-nuclear-reactors-for-faster-aircraft-carriers-and-in-flying-drones.html

[28] Halper, Mark, "U.S. partners with China on new nuclear", Smart Planet, June 26, 2012. Available at: http://www.smartplanet.com/blog/intelligent-energy/us-partners-with-china-on-new-nuclear/17037?tag=search-river.

[29] “Memorandum of Understanding between the Department of Energy of the United States of America and the Chinese Academy of Sciences on Cooperation in Nuclear Energy Sciences and Technologies,” signed December 21, 2011, in Washington DC, and December 29,2011 in Beijing, China.

[30] “Memorandum of Understanding between the Department of Energy of the United States of America and the Chinese Academy of Sciences on Cooperation in Nuclear Energy Sciences and Technologies,” signed December 21, 2011, in Washington DC, and December 29,2011 in Beijing, China.

Germany

Germany's TRISO pebble bed helium-cooled Thorium High Temperature Reactor (THTR) was a prototype commercial power station that used TRISO particles with fertile thorium kernels with fissile highly enriched U-235 fuel kernels. The THTR-300 reactor supplied electricity for 432 days in the late 1980s, before it was shut down for poor economics and some mechanical problems, including cracked pebbles because control rods were directly inserted into the core's central pebble region. On May 4, 1986, attempts by operators to dislodge a damaged pebble stuck in the pebble recirculation refueling piping resulted in a large radiation release. Under Germany's nuclear power phase-out policy, all operating nuclear plants will shut down by April 2023, and no new plants will be constructed.

India

Over the past 25 years, India has amassed significant experience utilizing thorium in nuclear reactors because of its significant thorium reserves, small uranium reserves, and increasing electricity demand. India has a three-stage nuclear power plan: (1) operate a number of Pressurized Heavy Water Reactors (PHWR) to generate plutonium, (2) use that plutonium in fast breeder reactors with fertile Th-232 to produce fissile U-233, and (3) then use the fissile U-233 fissile material in thorium-based PHWRs based entirely on thorium breeding and subsequent burning of U-233.[31,32] Reprocessing of irradiated thorium fuel in India's civilian and military HWRs creates unique safeguard challenges since India is not a member of the Nuclear Non-Proliferation Treaty.

India has operated commercial natural uranium fueled PHWRs for electricity generation and producing Pu-239 for many years. India has several research PHWRs (CIRUS, DHRUVA, KAMINI) to perform fuels and materials irradiation testing for ThO_2/UO_2 and ThO_2/PuO_2 fuels to support the thorium program or to use U-233 fuel directly.[33] The Fast Breeder Test Reactor (FBTR) was built as part of India's large-scale deployment of the fast reactor concepts and gave India confidence to begin construction of the Prototype Fast Breeder Reactor (PFBR) to be used as a final prototype reactor prior to large-scale deployment of fast breeder reactor. The 40 MW sodium-cooled FBTR utilizes mixed oxide (MOX) fuel pins that contain 30 percent PuO_2 and 70 percent UO_2 (85 wt% enriched) MOX fuel pins, with a large blanket region composed of assemblies filled with ThO_2. India operates several large scale PHWRs that use natural UO_2 fuel with ThO_2 or depleted UO_2 fuel bundles.

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[31] Majumdar, S.,D. Purushotham, "Experience of thorium fuel development in India," in IAEA-TECDOC-1319, "Thorium fuel utilization: Options and trends Proceedings of three IAEA meetings held in Vienna in 1997, 1998 and 1999," International Atomic Energy Agency (1999), pp. 69-76.

[32] Bucher, R. "India's Baseline Plan for Nuclear Energy Self-sufficiency," ANL/NE-09/03, Argonne National Laboratory (2009)

[33] Jha, Saurav, "Fuel for India's nuclear ambitions," Nuclear Engineering International, April 7, 2017. Available at: https://www.neimagazine.com/features/featurefuel-for-indias-nuclear-ambitions-5782668/.

India has 22 operating commercial reactors and is currently building 10 new reactors that use uranium and thorium-based fuel. The Government of India has also issued administrative and financial approvals for construction of 10 indigenous pressurized heavy water reactors to be built in a fleet mode.[34,35] In February 2014, Bhabha Atomic Research Centre (BARC), in Mumbai, India, introduced their latest design for a next-generation thorium-fueled reactor called the Advanced Heavy Water Reactor (AHWR),[36,37] which is summarized in Figure 3.1. Because of the inherent safety of the AHWR, BARC staff expect that similar designs could be set up close to or within populated cities, like Mumbai or Delhi. India has a detailed, funded, government-approved plan to focus on thorium-based nuclear power and has a thorium fuel infrastructure to support thorium reactor deployment.

Indonesia

A research division of the Indonesia Ministry of Energy and Mineral Resource has reviewed a thorium molten salt reactor by ThorCon called the TMSR-500. The study reported that building a ThorCon TMSR-500 would meet Indonesia's regulations for nuclear energy safety and performance.[38] However, no formalized safety or licensing review has been carried out by the Nuclear Energy Regulatory Agency of Indonesia. ThorCon is working with Indonesia on plans to build and test a prototype 500 MW TMSR with a step-by-step commissioning process, ending in a license approval for future Indonesia power plants.[39] In a second phase, several modular units would be shipyard-manufactured to provide up to an additional 3 GW of electric power.[40]

Norway

In 2012, Norway's privately owned Thor Energy, in collaboration with the Norwegian government and Westinghouse, announced a multi-year irradiation campaign using thorium

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[34] World Nuclear Association, “Nuclear Power in India, India Nuclear Energy,” May 2022, Available at: https://www.world-nuclear.org/information-library/country-profiles/countries-g-n/india.aspx.

[35] Department of Atomic Energy, “Union Minister Dr Jitendra Singh says, Government has accorded ‘In-Principle’ approval for five new sites for locating nuclear power plants in future,” April 6, 2022, available at: https://pib.gov.in/PressReleasePage.aspx?PRID=1814046.

[36] Ghunawat, V., “Design of world's first Thorium based nuclear reactor is ready,” India Today, February 2014. Available at: https://www.indiatoday.in/india/north/story/worlds-first-thorium-based-nuclear-reactor-barc-181107-2014-02-1.

[37] Jha, Saurav, “Fuel for India’s nuclear ambitions,” Nuclear Engineering International, April 7, 2017. Available at: https://www.neimagazine.com/features/featurefuel-for-indias-nuclear-ambitions-5782668/.

[38] P3Tek, Indonesia Ministry of Energy and Mineral Resource, “ P3Tek Recommends Thorcon Molten Salt Nuclear Reactor for Indonesia.” Available at: https://www.nextbigfuture.com/2019/09/p3tek-recommends-thorcon-molten-salt-nuclear-reactor-for-indonesia.html.

[39] World Nuclear News Association, “Bureau Veritas to help ThorCon develop Indonesian Plant,” World Nuclear News, Dec. 12, 2022, available at: https://www.world-nuclear-news.org/Articles/Bureau-Veritas-to-help-ThorCon-develop-Indonesian.

[40] ThorCon, “Indonesia ThorCon 3.5 GW fission power project,” and “ThorCon (ThorCon International, Indonesia).” Available at: https://thorconpower.com/project/ and https://thorconpower.com/docs/IAEAThorConPagesSMRBookletpdf.pdf.

fuel in the Halden Nuclear Reactor.[41] Thor Energy initiated and led the Thorium Irradiation Consortium which includes the Institute for Energy Technology , Norway, Westinghouse, Fortum (Finland), the United Kingdom's National Nuclear Laboratory, Institute for Transuranium Elements, and the Korea Atomic Energy Research Institute as consortium partners and has continued thorium fuel development. Three separate thorium fuel tests were completed in the Halden Reactor. The first thorium fuel specimens were inserted in April 2013, and the second round were loaded in December 2015, in order to provide transient test information as a step towards commercializing thorium for current LWRs. The third irradiation test started in 2018 had 3 new fuel pins, two evolutionary high-density Th-MOX fuel pins and one uranium oxide (UOX)-fuel reference.[42] The Halden Reactor shut down in 2018.

Russia

In 2020, Russian scientists proposed a concept of a thorium hybrid reactor that obtains additional neutrons using high-temperature plasma held in a long magnetic trap. This project was applied in close collaboration between Tomsk Polytechnic University, All-Russian Scientific Research Institute of Technical Physics (VNIITF), and Budker Institute of Nuclear Physics.[43] The proposed thorium hybrid reactor is distinguished from current reactor designs by moderate power, relatively compact size, high operational safety, and a low level of radioactive waste.

United Kingdom

The 20 MW Dragon high temperature helium-cooled gas reactor operated from 1964 to 1973 for 741 full power days as an OECD/Euratom cooperation project, involving Austria, Denmark, Sweden, Norway, and Switzerland in addition to the United Kingdom. Dragon used thorium-HEU fuel elements in a 'breed and feed' mode in which the U-233 formed during operation replaced the consumption of U-235 at about the same rate. Dragon's coated particle fuel used 1mm diameter uranium-thorium oxide kernels with silicon carbide and pyrolytic carbon coatings that could operate at high temperatures for high burnup levels and contain fission products during normal and accident conditions. The particles were compacted in 45 mm long graphite elements, which could be used to produce power in the reactor for roughly six years.[44]

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[41] Halper, Mark, "Norway ringing in thorium nuclear New Year with Westinghouse at the party," Smart Planet, Nov. 23, 2012. Available at: https://www.zdnet.com/article/norway-ringing-in-thorium-nuclear-new-year-with-westinghouse-at-the-party

[42] Røst, Sven "Next Generation thorium mixed oxide fuel pellets loaded into reactor for testing," Thor Energy, Feb. 6, 2018. Available at: http://thorenergy.no/new-generation-thorium-mixed-oxide-fuel-pellets-loaded-into-reactor-for-testing/.

[43] Tomsk Polytechnic University, "Scientists develop a concept of a hybrid thorium reactor," Phys.org News, January 29, 2020, available at: https://phys.org/news/2020-01-scientists-concept-hybrid-thorium-reactor.html.

[44] Simon, R.A.; Capp, P.D., "Operating experience with the DRAGON High Temperature Reactor experiment," IAEA. INIS-XA--524, 2021. Available at: https://inis.iaea.org/collection/NCLCollectionStore/_Public/33/033/33033056.pdf.

Summary

Thorium fuels were used in large commercial-scale cores in HGTRs, MSRs, BWRs, and PWRs in some countries. However, currently, India is the only country with large-scale operating thorium fueled PHWRs producing electricity. As of 2022, there are no large-scale operating thorium molten salt reactors in the world. The historic database and experience information for thorium fueled reactors and thorium fuel cycles are limited and would need to be augmented significantly before any large-scale future U.S. commercial deployment of thorium-fueled reactors. Demonstration and/or prototype thorium reactors using Generation IV (Gen IV) reactor designs would need to be deployed to gain sufficient operating experience before any commercial deployment in the U.S.

Future advanced thorium-fueled reactor designs could use various coolants, as well as fuel element types and configurations, and operate at different temperature ranges for diverse applications, as shown in Table 3.2 and are described below:

- LWRs could use: (a) thorium seed blanket fuel in a once-through high burnup thorium cycle in ThO_2 and (Th, U-235)O_2 (LEU) 'pellet-pin' fuel assemblies, (b) Cermet fuel consisting of fuel microspheres of (Th, U-235)O_2 (LEU) encased in a zirconium matrix rod, and/or (c) thorium-plutonium 'pellet-pin' fuel assemblies for burning civilian and weapons plutonium in 'once-through' high burnup fuel cycle.[45]

- HTGRs using thorium kernels in TRISO multilayer coatings, in some cases using ZrC coating in place of SiC layers, Thorium-based or thorium mixed oxide or dicarbide kernels could be used either in pebble form or in compacts inside prismatic graphite blocks and operate at very high temperatures (800–1000 C) for high process heat applications (e.g., hydrogen generation, petrochemical processes).

- Fast reactors would use (Th, Pu)O_2 'pellet-pin' fuel assemblies in a once-through open cycle to burn weapons or civilian plutonium and simultaneously make the spent fuel proliferation-resistant because neutron capture in Th-232 would produce U-232, making U-233 separations extremely difficult.

- MSRs would use mixed fluoride molten salt with uranium and thorium in a composition of $Li_7F/BeF_2/ThF_4/UF_4$ for a self-sustaining (i.e., breeding) Th-232/U-233 fuel cycle. The initial MSR fuel would use LEU with thorium until sufficient U-233 is produced.

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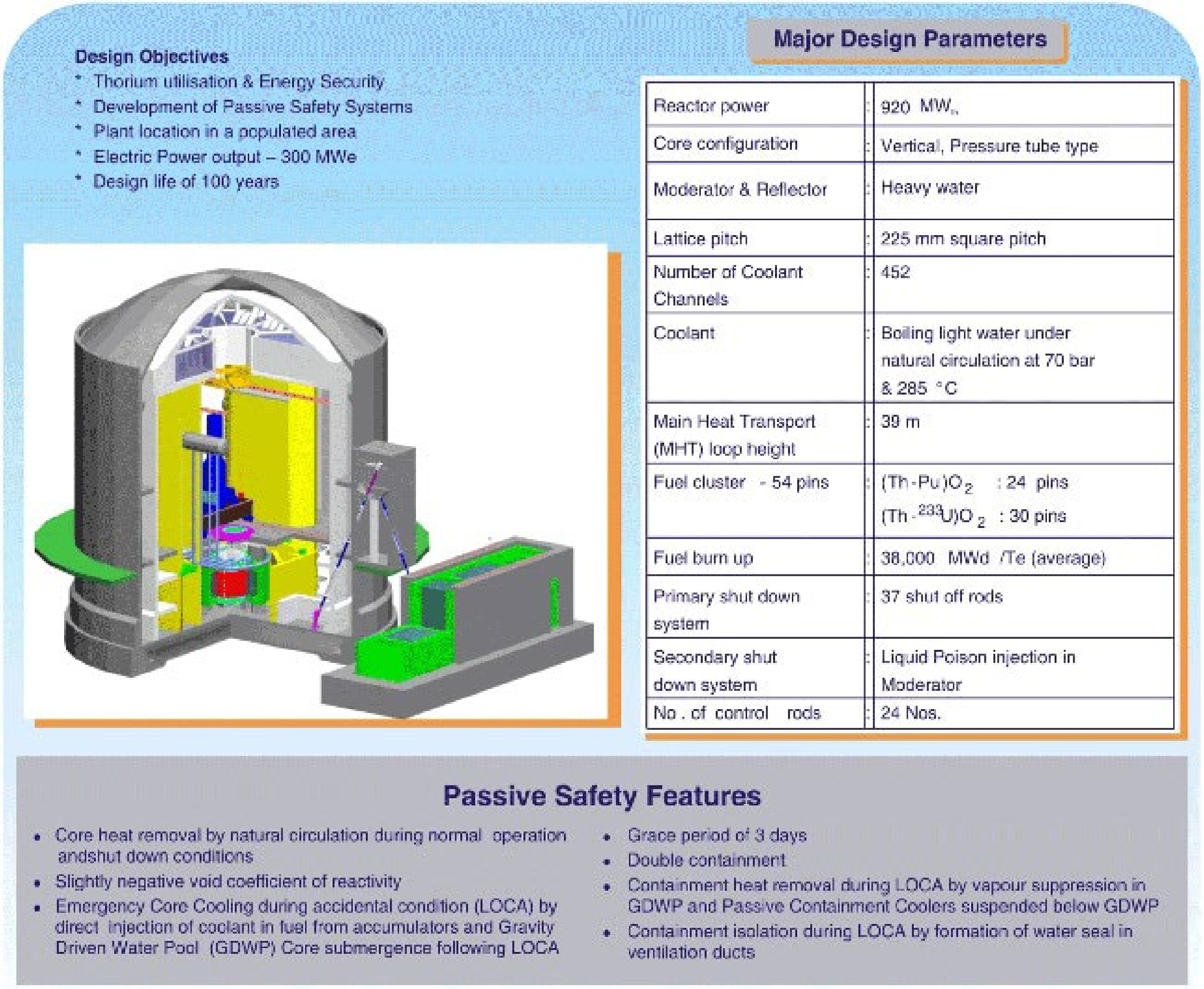
[45] Radkowsky, Alvin, Alex Galperin, "The Nonproliferative Light Water Thorium Reactor: A New Approach to Light Water Reactor Core Technology," Nuclear Technology, Vol 124, December 1998, pp. 215-222.

- PHWRs such as the thorium-fueled Advanced Fuel CANDU concept and the Indian AHWR design shown in Figure 3.1, would use pellet-pin fuel assemblies and not need to use enriched uranium.

Figure 3.1 **India's Advanced Heavy Water Reactor Design**[46]



Design Objectives

- Thorium utilisation & Energy Security
- Development of Passive Safety Systems
- Plant location in a populated area
- Electric Power output – 300 MWe
- Design life of 100 years

Major Design Parameters

Reactor power	920 MW_{th}
Core configuration	Vertical, Pressure tube type
Moderator & Reflector	Heavy water
Lattice pitch	225 mm square pitch
Number of Coolant Channels	452
Coolant	Boiling light water under natural circulation at 70 bar & 285 °C
Main Heat Transport (MHT) loop height	39 m
Fuel cluster - 54 pins	$(Th-Pu)O_2$: 24 pins $(Th-^{233}U)O_2$: 30 pins
Fuel burn up	38,000 MWd /Te (average)
Primary shut down system	37 shut off rods
Secondary shut down system	Liquid Poison injection in Moderator
No . of control rods	24 Nos.

Passive Safety Features

- Core heat removal by natural circulation during normal operation andshut down conditions
- Slightly negative void coefficient of reactivity
- Emergency Core Cooling during accidental condition (LOCA) by direct injection of coolant in fuel from accumulators and Gravity Driven Water Pool (GDWP) Core submergence following LOCA
- Grace period of 3 days
- Double containment
- Containment heat removal during LOCA by vapour suppression in GDWP and Passive Containment Coolers suspended below GDWP
- Containment isolation during LOCA by formation of water seal in ventilation ducts

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[46] Ghunawat, V., "Design of world's first Thorium based nuclear reactor is ready," India Today, February 2014. Available at: https://www.indiatoday.in/india/north/story/worlds-first-thorium-based-nuclear-reactor-barc-181107-2014-02-1.

Table 3.1 Thorium-fueled test and power reactors[47]

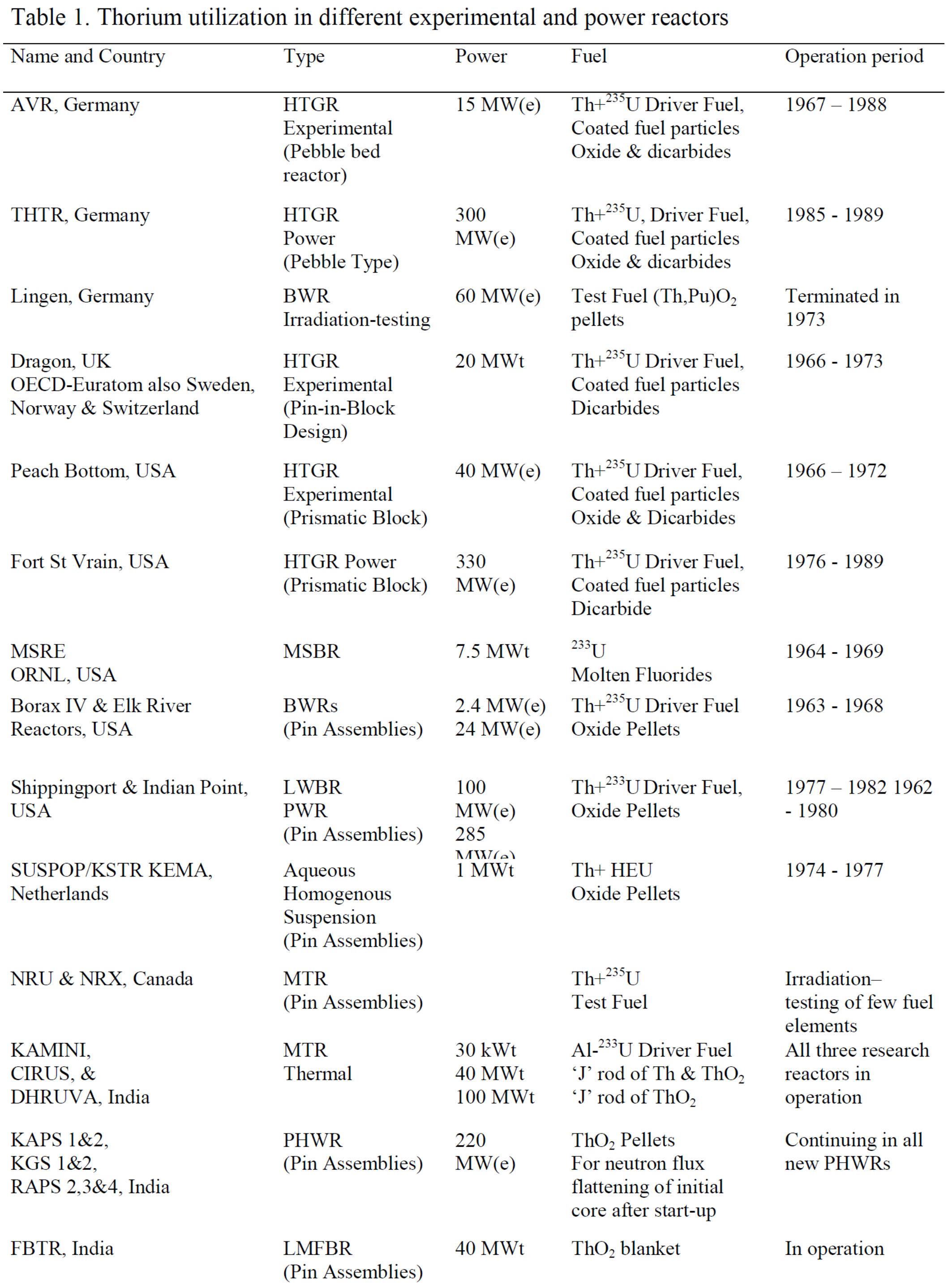

Table 1. Thorium utilization in different experimental and power reactors

Name and Country	Type	Power	Fuel	Operation period
AVR, Germany	HTGR Experimental (Pebble bed reactor)	15 MW(e)	Th+^{235}U Driver Fuel, Coated fuel particles Oxide & dicarbides	1967 – 1988
THTR, Germany	HTGR Power (Pebble Type)	300 MW(e)	Th+^{235}U, Driver Fuel, Coated fuel particles Oxide & dicarbides	1985 - 1989
Lingen, Germany	BWR Irradiation-testing	60 MW(e)	Test Fuel (Th,Pu)O_2 pellets	Terminated in 1973
Dragon, UK OECD-Euratom also Sweden, Norway & Switzerland	HTGR Experimental (Pin-in-Block Design)	20 MWt	Th+^{235}U Driver Fuel, Coated fuel particles Dicarbides	1966 - 1973
Peach Bottom, USA	HTGR Experimental (Prismatic Block)	40 MW(e)	Th+^{235}U Driver Fuel, Coated fuel particles Oxide & Dicarbides	1966 – 1972
Fort St Vrain, USA	HTGR Power (Prismatic Block)	330 MW(e)	Th+^{235}U Driver Fuel, Coated fuel particles Dicarbide	1976 - 1989
MSRE ORNL, USA	MSBR	7.5 MWt	^{233}U Molten Fluorides	1964 - 1969
Borax IV & Elk River Reactors, USA	BWRs (Pin Assemblies)	2.4 MW(e) 24 MW(e)	Th+^{235}U Driver Fuel Oxide Pellets	1963 - 1968
Shippingport & Indian Point, USA	LWBR PWR (Pin Assemblies)	100 MW(e) 285 MW(e)	Th+^{233}U Driver Fuel, Oxide Pellets	1977 – 1982 1962 - 1980
SUSPOP/KSTR KEMA, Netherlands	Aqueous Homogenous Suspension (Pin Assemblies)	1 MWt	Th+ HEU Oxide Pellets	1974 - 1977
NRU & NRX, Canada	MTR (Pin Assemblies)		Th+^{235}U Test Fuel	Irradiation–testing of few fuel elements
KAMINI, CIRUS, & DHRUVA, India	MTR Thermal	30 kWt 40 MWt 100 MWt	Al-^{233}U Driver Fuel 'J' rod of Th & ThO_2 'J' rod of ThO_2	All three research reactors in operation
KAPS 1&2, KGS 1&2, RAPS 2,3&4, India	PHWR (Pin Assemblies)	220 MW(e)	ThO_2 Pellets For neutron flux flattening of initial core after start-up	Continuing in all new PHWRs
FBTR, India	LMFBR (Pin Assemblies)	40 MWt	ThO_2 blanket	In operation

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[47] Sokolov, F., K. Fukuda, H. P. Nawada, "Thorium Fuel Cycle—Potential Benefits and Challenges," IAEA-TECDOC-1450, International Atomic Energy Agency (2005).

Table 3.2 Fuel Cycles Comparison for Light Water Reactors (LWRs) and Molten Salt Reactors (MSRs) and Heavy Water Reactors (HWRs)[48]

Fuel cycle	Uranium based and once-through	Uranium-plutonium based and limited recycle	Thorium-uranium based, continuous recycle, and online continuous recycle
Key nuclear materials of interest	U (natural uranium and LEU)	U and Pu	U, Pu, Th, and ^{233}U
Fuels/mechanical design	UO_2 simple pin-based square fuel assembly	MOX simple pin-based square fuel assembly	Numerous options, including pin-based driver blanket, combined fuel assemblies, heterogeneous fuels including particle fuel or pebble fuel, and liquid fuels
Infrastructure	Enrichment (LEU fuel) and no separation technology	Enrichment (LEU fuel) and separation technology (^{239}Pu)	Enrichment (LEU for highly enriched uranium fissile driver) and separation technology (^{233}U)
Reactors	LWRs	LWRs	LWRs, MSRs, and HWRs[a]

[a]HWRs = heavy water reactors.

IV. Office of Nuclear Energy Thorium Research and Development

Although DOE does not have an ongoing thorium reactor development program, the Office of Nuclear Energy (NE) has sponsored several thorium-related research projects in the past as part of NE's university programs, in Nuclear Energy University Program (NEUP) projects, as shown in Table 4.1, in previous Nuclear Energy Research Initiative (NERI) projects, as shown in Table 4.2 and as part of NE's Gateway for Accelerated Innovation in Nuclear (GAIN), as shown in Table 4.3. The university led NEUP and NERI research grant projects will be described briefly here, but details about each one can be found at: https://neup.inl.gov/SitePages/Home.aspx where the abstracts and final reports are provided. General information about GAIN can be found at: https://gain.inl.gov/SitePages/Home.aspx and specific GAIN thorium-related information can be found at: https://gain.inl.gov/VoucherSummaries/Forms/AllItems.aspx and https://gain.inl.gov/SiteAssets/Funding%20Opportunities/NE_VoucherRecipientsConsolidated_4.11.2022.pdf.

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[48] Worrall, Louise G., A Worrall, G. F. Flanagan, et al., "Safeguards Considerations for Thorium Fuel Cycles," Nuclear Technology, Vol 194, No. 2, May 2016, pp. 281-293.

Nuclear Energy University Program

In 2011, University of California (UC) Berkeley began studies for self-sustaining thorium BWR core designs (NEUP 2011-3023) that innovate on historical compact-lattice LWR designs to improve neutronic efficiency that would use thorium instead of depleted uranium as the primary fertile fuel along with enriched uranium as the fissile fuel. Thorium fueled cores would allow for a harder, fast neutron spectrum BWR design without having high neutron leakage axial fissile zones, internal fuel blanket regions, and parasitic neutron absorber materials in the axial reflector region and achieve better fuel efficiency. The following year, UC Berkeley initiated research (NEUP 2012-3486) to assess the feasibility of using thorium-fueled “breed and burn” blanket regions to generate U-233 fissile fuel to improve the economics and transmutation of transuranic fuel in an advanced burner fast sodium-cooled reactor design.

Starting in 2012, Georgia Tech investigated fuel and core design options for liquid salt-cooled reactors (NEUP-2012-3870) to keep the uranium enrichment below the 20 percent LEU limit by examining a broad range of fuel assembly and core designs that also included the use of high conversion Thorium-U-233 cycle cores to alleviate the reactivity swings during long fuel cycles. Georgia Tech’s Integrated Research Project (NEUP 12-4733) for the Integral Inherently Safe Light Water Reactor (I^2S-LWR) included collaborators from various U.S. and international universities. In addition to ten U.S. research organizations, partners from the United Kingdom, Italy, and Croatia brought expertise to the project in a variety of different technical fields including reactor physics, thermal-hydraulics and safety, and thorium-based fuels technology. Cambridge University was sponsored by the United Kingdom Engineering and Physical Sciences Research Council and studied thorium-based fuels for use in the I^2S-LWR reactor. Although thorium fuel is not a priority in the United States, thorium fuels are of high interest to United Kingdom academics, allowing both countries to leverage the project for their own priorities and research interests.

Vanderbilt University developed fuel cycle data packages for six specific thorium fuel cycle options (NEUP 2013-5220) and then organized an international technical symposium on the thorium fuel cycle. The Thorium Fuel Cycle Database was established by using documents from the symposium and it continues to expand using thorium fuel cycle literature making it a centralized accessible reference source available at the ORNL.[49] This database can be used in conjunction with ORNL’s software packages such as SCALE and ORIGEN to evaluate thorium core reactor physics and fuel cycle options.

As part of nuclear material control and accounting (MC&A) requirements to meet NRC licensing and international nonproliferation standards and to facilitate future international reactor exports, University of Tennessee began development of an MC&A “toolbox” (NEUP 2018-

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[49] Krahn, Steven, Ault, Timothy, and Worrall, Andrew. DE-NE0000735 - FINAL REPORT ON THORIUM FUEL CYCLE NEUP PROJECT. United States: N. p., 2017. Web. doi:10.2172/1400239, available at: https://www.osti.gov/biblio/1400239.

15061) specifically for liquid salt fueled reactors that would include online fuel reprocessing, for both uranium and thorium-fueled MSRs. MSRs have a very broad range of design parameters including thermal and fast neutron spectrum designs, operations either as actinide breeders or burners, pool or loop type configurations, different salt chemistry (e.g., fluoride or chloride salts) and the choice of the fuel used (e.g., U-235, Th-232/U-233, denatured U-233, Th/U/Pu, etc.). The University of Tennessee team worked with Sandia National Laboratories to develop a modular, component-based test bed to explore viable process monitoring and MC&A techniques to determine dynamic physical signatures to measure and model salt fuel mass flow conditions.

Nuclear Energy Research Initiative

Prior to the NEUP program, NE had university and laboratory-led research projects in the Nuclear Energy Research Initiative (NERI) which started in 1999. Several NERI projects focused on thorium fuel and thorium-fueled reactor designs and are listed in Table 4.2.

Idaho National Laboratory (INL), Argonne National Laboratory (ANL), and Massachusetts Institute of Technology along with other researchers developed mixed homogeneous Th/U dioxide fuels that could be used in current and future commercial LWRs (NERI 99-0153) by performing reactor physics, thermal-hydraulics, economics, and fuel waste cycle analysis. This NERI project produced many publications, including 13 journal papers in a special issue volume of *Nuclear Technology*, vol. 147, July 2004. In a related project, Brookhaven National Laboratory (BNL) developed and optimized Th/U/Pu fuel designs in PWR cores to enhance proliferation resistance and reduce spent fuel waste (NERI 2000-014). This NERI project used the standard Westinghouse 17x17 fuel assembly configuration to be able to retrofit current PWRs and future AP600/AP1000 PWRs. A novel proliferation resistant tight lattice BWR fuel core design was developed (NERI 99-0164) to be able to increase burnup and reduce spent fuel storage volumes. This project performed detailed reactor physics, economics, and coupled thermal hydraulic and neutronics analyses for a tight-lattice high conversion BWR fuel with Pu and fertile thorium oxide elements.

ANL worked with Purdue University (NERI 99-095) to investigate Th/U oxide fuel microspheres dispersed in a zirconium metal matrix cermet fuel to enhance burnup and heat transfer capability and demonstrated fabrication techniques and its potential for LWR fuel retrofits. The use of solid hydride fuel, similar to TRIGA research reactor fuel, was studied in order to improve LWR core designs (NERI 2002-189). The team examined the use of solid hydride fuels or solid hydride fuel inserts with U-ThH2, or Pu-ThH2 and analyzed use of thorium fuel resources, increased burnup, core reactor physics, safety, and materials compatibility issues, and U-233 and Pu proliferation resistance.

Gateway for Accelerated Innovation in Nuclear

In 2018, ThorCon (Stevenson, WA) was awarded two GAIN vouchers for their thermal neutron spectrum thorium/uranium MSR known as the ThorConIsle power plant, based on the ORNL MSR experiments performed in the 1960's. The ThorCon reactor concept is not a breeder reactor but requires additions of uranium fluoride and beryllium metal to continue the fission process and maintain redox chemistry control. Working with ANL, ThorCon is quantifying Sodium Fluoride/Beryllium Fluoride salt thermophysical property data (NE-18-16098) and developing multi-function electroanalytical sensors (RFA-18-15820) to be able to maintain proper redox conditions to minimize corrosion in the core and reactor structures.

Flibe Energy (Madison, Alabama) initiated two GAIN projects in 2019 for their Liquid Fluoride Thorium Reactor (LFTR) concept, which is an innovative two-fluid MSR coupled to a closed-cycle gas turbine for power generation. The LFTR is started with high U-233 content fuel and does not require fissile uranium to be added during its operation and uses an internal chemical process to purify the fuel salt and remove fission products. This approach introduces unique proliferation safeguards challenges with its high U-233 content and high radiation field that complicates inspection access. Flibe is working with ORNL (NE-19-18380) to develop safeguards technologies and assess possible LFTR design changes to accommodate nonproliferation issues. Working with Pacific Northwest National Laboratory (PNNL), the second Flibe Energy project (NE-19-18706) is investigating the active removal of fission product xenon from the off-gas system for the thorium-bearing molten salt that has noble gases as it operates. This will allow the LFTR reactor design to be able to achieve dynamic load-following maneuvers for flexible power operations.

DOE's National Laboratories engage in CRADAs with U.S. and foreign commercial companies, foreign national research organizations, etc., to perform research and development activities as requested. In May 2022, a CRADA between Clean Core Thorium Energy (Illinois) and INL was approved to work with Canadian researchers to irradiate thorium-bearing ceramic fuel in the INL Advanced Test Reactor (ATR) and perform post irradiation examinations.[50]

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[50] AP News Globe Newswire, "Clean Core Thorium Energy and U.S. Department of Energy Sign Strategic Partnership Agreement," June 14, 2022. Available at: https://apnews.com/press-release/globe-newswire/technology-business-us-department-of-energy-climate-and-environment-568dafb08ddb98aa96ceda5b84d27cc9

Table 4.1 Thorium-related NEUP projects

NEUP Project Year - Number	Project Title	Principal Investigator, University
2011-3023	Self-Sustaining Thorium Boiling Reactors	Greenspan, UC Berkeley
2012-3486	Advanced Burner Reactor (ABR) for TRU Transmutation with Breed and Burn Blanket for Improved Economics and Resource Utilization	Greenspan, UC Berkeley
2012-3870	Fuel and Core Design Options to Overcome the Heavy Metal Loading Limit and Improve Performance and Safety of Liquid Salt Cooled Reactors	Petrovic, Georgia Institute of Technology
2012-4733	Integral Inherently Safe Light Water Reactor (I^2S-LWR) (Integrated Research Project)	Petrovic, Georgia Institute of Technology Ricotti, Cambridge Univ.
2013-5220	Development of Fuel Cycle Data Packages for Thorium Fuel Cycle Options	Krahn, Vanderbilt University
2018-15061	Development of an MC&A Toolbox for Liquid-Fueled Molten Salt Reactors with Online Reprocessing	Stutnik, University of Tennessee

Table 4.2 Thorium-Related NERI Projects

NERI Project Year - Number	Project Title	Principal Investigator, University, Laboratory
1999-0153	Advanced Proliferation Resistant, Lower Cost, Uranium-Thorium Dioxide Fuels for Light Water Reactors	MacDonald, INL, ANL, MIT
1999-095	Fuel for a Once Through Cycle (Th,U)O2 in a Metal Matrix	McDeavitt, ANL, Purdue
1999-0164	A Proliferation Resistant Hexagonal Tight Lattice BWR Fuel Core Design for Increased Burnup and Reduced Fuel Storage Requirements	Takahashi, BNL, Purdue, Hitachi.
2000-014	Optimization of Heterogeneous Schemes for the Utilization of Thorium in PWRs to Enhance Proliferation Resistance and Reduce Waste	Todosow, BNL
2002-189	Use of Solid Hydride Fuel for Improved Long-Life LWR Core Designs	Greenspan, Univ. of CA, MIT

Table 4.3 Thorium-related GAIN projects

GAIN Project Year - Number	Project Title	Voucher Recipient Partner Facility
RFA-18-15820	Electroanalytical Sensors for Liquid Fueled Fluoride Molten Salt Reactor	ThorCon ANL
NE-18-16098	Quantify Sodium Fluoride/Beryllium Fluoride Salt Properties for Liquid Fueled Fluoride Molten Salt Reactors	ThorCon ANL
NE-19-18380	Liquid Fluoride Thorium Reactor (LFTR) Preliminary Safeguards Assessment	Flibe Energy ORNL
NE-19-18706	Metal Organic Frameworks for Noble Gas Management in the Liquid Fluoride Thorium Reactor	Flibe Energy PNNL

V. Benefits, Challenges, and Economics of the Thorium Fuel Cycle

The thorium fuel cycle offers long-term energy security benefits because of its potential for being a self-sustaining fuel without the need for fast neutron reactors. Thorium fuel technology may become a potentially viable means to build a credible, long-term nuclear energy future. Thorium-fueled reactors may have many potential advantages. The primary advantage would be that a thorium fuel cycle would produce fissile U-233 that could be then used as "driver" fuel for the unirradiated fertile Th-232 fuel while producing less plutonium and other transuranic long-lived radioactive isotopes and toxic waste than conventional light water reactors (LWRs). The economics of implementing a thorium-based fuel cycle pose both advantages and disadvantages when compared to conventional uranium and plutonium fuel cycles. There are many technical benefits, advantages, disadvantages, and challenges for the thorium fuel cycle and thorium-fueled reactor designs,[51,52] which are described below:

Thorium-fueled Reactor Benefits

1. Reduction in uranium enrichment requirements

Although a thorium reactor can initially be fueled with natural and enriched uranium, eventually there is a reduced need for further uranium enrichment when sufficient U-233 has been produced in the thorium fuel. Almost all thorium is fertile Th-232 and does not need to be enriched, versus natural uranium which is composed of 99.3 percent fertile U-238 and 0.7 percent more valuable fissile U-235 and must be enriched to 5 percent U-235 for current LWR fuel, or up to 19.75 percent for future advanced uranium reactor designs.

2. Enhanced reduction of weapons-usable plutonium isotopes

Spent thorium fuel has reduced plutonium isotope concentrations, which enhances Pu proliferation resistance. Several thorium-fueled nuclear reactor concepts are designed to burn spent uranium fuel to consume plutonium and uranium spent fuel isotopes and could be used to incinerate weapons-grade plutonium. Superior plutonium incineration in (Th, Pu) O_2 fuel may be possible in thorium reactors as compared to (U, Pu) O_2 mixed oxide fuel in LWRs.

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[51] Sokolov, F., K. Fukuda, H. P. Nawada, "Thorium Fuel Cycle—Potential Benefits and Challenges," IAEA-TECDOC-1450, International Atomic Energy Agency (2005).

[52] Gaille, Louise, "16 Big Thorium Reactor Pros and Cons," Vittana.org, January 10, 2018. Available at: https://vittana.org/16-big-thorium-reactor-pros-and-cons.

3. Plentiful thorium resources

Thorium is at least three times more available than uranium, so there is enough thorium to fuel the world's power reactors. In the U.S., there is an estimated supply of thorium that could meet current energy needs for the next 1,000 years, and about 25,000 metric tons of thorium globally. Most of the available thorium inventory could be recovered easily from monazite mining tails as a byproduct of rare earth element extraction at low prices because radioactive thorium-laden mining wastes are considered a storage burden. Chapter 9 and Appendix B give details about thorium sources in the U.S. and globally.

4. Thorium fuel utilization could reduce nuclear spent fuel volume and waste radiotoxicity

Current spent uranium and plutonium fuel can be recycled and can be combined with thorium-based fuel to be burned in thorium reactors. The LWR irradiated uranium fuel can be recycled to make fissile driver U/Pu fuel to be combined with fertile thorium fuel. Current estimates for LWR nuclear storage are up to 100,000 years of maintenance. With thorium spent fuel, the estimated time might be 300 years. The generation of transuranic minor actinide elements (neptunium, plutonium, americium, and curium), which constitute most of the radiotoxic inventory from the spent fuel after a few centuries is lower for the fully closed thorium/U-233 fuel cycle than for the conventional uranium-only fuel cycle. However, this is likely not to be the case for thorium-plutonium fueled reactors and is less clear for thorium-LEU fuel designs. Thorium utilization may reduce the volume and need for large-scale spent fuel storage facilities as the technology for reusing nuclear fuels is improved. Some estimate that the threat of hazardous waste from a thorium reactor will be at least 1,000-10,000 times less than comparable uranium-based technologies that are currently in use in LWRs.[53] Thus, the thorium fuel cycle is a potential way to produce long term nuclear energy with low radiotoxicity waste, as shown in Figures 5-1 and 5-2.

5. Thorium fuel may have higher overall energy efficiency levels than uranium fuel or fossil-fueled technologies

Thorium fuel can produce more energy with efficiency levels as high as 98 percent in terms of total fuel burnup levels as irradiation of thorium fuel produces fissile U-233, which can be used further to produce power. Current LWR fuel produce lower amounts of energy since the U-235 enrichment limit is 5 percent, and irradiated LWR fuel produces some fissionable plutonium isotopes that can produce power later in the core lifetime. This means thorium fuel has the potential to produce more energy than any current traditional fossil-fuel based option, current uranium fuel technologies, and renewable power resources. The benefit of a thorium reactor is that just one ton of thorium can produce as much energy as an estimated 200 tons of uranium.

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[53] Hargraves, Robert and Moir, Ralph. "Liquid Fluoride Thorium Reactors: An old idea in nuclear power gets reexamined", American Scientist, Vol. 98, p. 304 (2010). Available at: http://www.ralphmoir.com/wp-content/uploads/2012/10/hargraves2010_2.pdf

When thorium is compared to coal-fired power plants, the difference is much greater. One ton of thorium can create the same amount of energy as 3.5 million tons of coal.[54]

6. Thorium oxide fuels may have better irradiation performance than uranium oxide fuels

ThO_2 is chemically more stable and has higher radiation resistance than uranium dioxide (UO_2). The fission product release rate for ThO_2–based fuels is one order of magnitude lower than that of UO_2. ThO_2 has favorable thermophysical properties because of higher thermal conductivity and lower coefficient of thermal expansion compared to UO_2.[55] Finally, ThO_2 fuel exhibits better thermo-physical properties and chemical stability, as compared to uranium dioxide UO_2, which ensures better in-pile performance and a more stable waste form. Thus, ThO_2–based fuels are expected to have better in–pile performance than UO_2 fuel.

7. Thorium fueled molten salt reactors may have improved safety features

TMSRs operate at atmospheric pressure, potentially reducing leak rates in a system breach.[56] Liquid fluoride MSR thorium reactors may be designed to be meltdown-resistant by using a fusible plug at the bottom of the reactor that melts in the event of a power failure or if temperatures exceed a set limit, draining the thorium fuel salt coolant mixture into an underground tank for safe, non-critical geometry storage.

8. Mining thorium is safer and more efficient than mining uranium

Monazite ore contains higher concentrations of thorium when compared to uranium ore in its respective natural state, thus making direct thorium pit mining or thorium extraction from monazite mining tails and waste streams more efficient, less costly, and potentially safer. The threat of high radon levels that are found in underground uranium mines is greater than that of direct thorium open pit mining.

Challenges for Thorium-fueled Reactors

1. No current U.S. infrastructure to support thorium fuel utilization exists

In the United States, thorium research and development has been minimal for more than 30 years, so that DOE laboratory experience would have to be gained and/or enhanced. The U.S. laboratories and nuclear industry does not have the required infrastructure to fabricate, ship,

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[54] Gaille, Louise, "16 Big Thorium Reactor Pros and Cons," Vittana.org, January 10, 2018. Available at: https://vittana.org/16-big-thorium-reactor-pros-and-cons.

[55] Nuclear Energy Agency, "Background Note for the Policy Debate on the Thorium Fuel Cycle Briefing for the Delegates," OECD NEA/SEN (2014)2, Oct. 7, 2014.

[56] Elsheikh, Badawy M., "Safety assessment of molten salt reactors in comparison with light water reactors," Journal of Radiation Research and Applied Sciences, Volume 6, Issue 2, October 2013, Pages 63-70.

or use thorium-based fuels. The NRC would need to perform confirmatory research experiments and develop sufficient information to approve potential thorium-fueled reactor designs and fuel cycle facilities.

2. Not every thorium fuel design is self-sustaining

Not every thorium reactor design can produce as much fissile material as it consumes while generating energy. Some non-breeding reactor designs require the addition of new fissile materials, such as U-235 and plutonium, to maintain production levels. That reduces many of the benefits that a thorium reactor would be able to deliver once it becomes operational. Closed thorium fuel cycle breeding reactors would produce at least as much fissile material (U-233) as they consume, so once started, no additional fuel except fertile thorium 232 would be needed;[57] however, the time to reach equilibrium between U-233 production and consumption may take many years.

3. Thorium fuel radioactive decay products and created fissile U-233 could pose unique hazards and proliferation issues

A full thorium fuel cycle would use U-233 and irradiated thorium to produce energy. When thorium is irradiated, it creates U-232. This material produces high levels of dangerous gamma rays, even if certain nuclear threats are eliminated. The U-233 fuel can be used in nuclear weapons, which eliminates the main reason for transitioning to this technology for many in the first place, i.e., reduction of Pu isotopes from uranium-only fuel.

4. Thorium fuel reprocessing is more difficult than uranium fuel reprocessing

Irradiated ThO_2 and spent ThO_2 fuels are very difficult to reprocess and dissolve in HNO_3 because ThO_2 is more stable and chemically inert. The high gamma radiation associated with the short-lived daughter products of U-232, which is always associated with U-233, necessitates remote handling, reprocessing, and refabrication of fuel. The protactinium formed in thorium fuel cycle also causes reprocessing problems, which need to be resolved.

5. Research into thorium energy is limited

Historically, thorium fuel research and thorium reactor deployment has been limited because of the possible proliferation concerns over U-233 production. Although thorium research has occurred in the U.S., Germany, Denmark, and other countries, only India and China are actively pursuing thorium fuel technology with an intent to utilize it in the near future. India has

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[57] Moir, Ralph W., Edward Teller, “Thorium-Fueled Underground Power Plant Based on Molten Salt Technology,” Nuclear Technology, Vol. 151, No. 3, Sept. 2005, pp. 334-340.

produced U-233 for nuclear weapons in civilian and military reactors. China is actively pursuing military applications.[58,59,60]

6. Molten salt reactors pose unique technology challenges

Although MSRs offer potential improvements in reactor safety[61] such as having a stable non-boiling coolant and operating at low pressure that eliminates the need to have an expensive containment, there are technology challenges. The molten salt can be very corrosive and erode piping and equipment, so that salt chemistry and circulating fission products must be controlled carefully. Continuous chemical cleanup systems are needed to remove contaminants and fission products that parasitically absorb neutrons and create corrosion issues. Chemical extraction and diversion of U-233 using these chemical cleanup systems can lead to proliferation problems. Modelling the fissile and fertile fuel isotopes, neutron burnup concentration conditions, radionuclides and chemical species that must be tracked for accidental release dynamics and source term analysis is very complicated. Sophisticated MSR license safety analysis tools will have to be developed, benchmarked against actual physical data, and accepted by the NRC.

7. Thorium fuel fabrication, reactor deployment, recycling, and utilization may cost more than uranium

Because there is no existing U.S. infrastructure in place to support thorium fuel technologies, many of the anticipated costs are only speculative and could be much higher. In 2004, the proposed cost for deploying a new prototype system in the United States was listed as being "less than $1 billion" with operational costs of about $100 million per year.[62] Thorium fuel fabrication costs may be higher when compared to traditional nuclear technologies. Standard fuel rods may have waste storage challenges and high fabrication costs, but even with current technology, it is still cheaper to generate power with uranium fuel rods than it would be to fabricate thorium fuel for energy production. Moir[63] compares cost of electricity production for thorium MSRs, pressurized water reactors and coal plants delineating specific costs (i.e., construction, capital, fuel, operations, maintenance, waste disposal, decommissioning, etc.) on a per kilowatt hour basis and concludes thorium closed fuel cycle MSRs are less costly. A

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[58] Wang, Brian, "China spending U.S. $3.3 billion on molten salt nuclear reactors for faster aircraft carriers and in flying drones," Next Big Future, December 2017

[59] Seibt, Sébastian, "Why China is developing a game-changing thorium-fuelled nuclear reactor," Dec. 9, 2021, France24.com, available at: https://www.france24.com/en/asia-pacific/20210912-why-china-is-developing-a-game-changing-thorium-fuelled-nuclear-reactor

[60] "Chinese molten-salt reactor cleared for start up," New Nuclear section, World Nuclear News, August 9, 2022, available at: https://www.world-nuclear-news.org/Articles/Chinese-molten-salt-reactor-cleared-for-start-up

[61] Elsheikh, Badawy M., "Safety assessment of molten salt reactors in comparison with light water reactors," Journal of Radiation Research and Applied Sciences, Volume 6, Issue 2, October 2013, Pages 63-70.

[62] Moir, Ralph W., Edward Teller, "Thorium-Fueled Underground Power Plant Based on Molten Salt Technology," Nuclear Technology, Vol. 151, No. 3, Sept. 2005, pp. 334-340.

[63] Moir, Ralph, "Cost of Electricity from Molten Salt Reactors," Nuclear Technology, Vol. 138, April 2002, pp. 93-95.

qualitative comparison between uranium/plutonium versus thorium fuel cycle costs is described next.

Given that the thorium fuel cycle has not been deployed on an industrial scale in the US, there is: (a) no accurate data on the costs associated with the different stages of this cycle, (b) no supply chain of thorium, and consequently, (c) no indexed thorium market or cost projections. However, it is possible to estimate general thorium economic trends for thorium utilization by comparing them with conventional fuel cycle costs at different stages. Using a French large industrial scale reference case for a closed uranium/plutonium fuel cycle implementation[64] the following cost breakdown data can be used to qualitatively compare thorium cycle costs, as shown on Table 5-1, and described in the notes below:

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[64] Ministère de l'Économie, des Finances et de l'Industrie (1997), Coûts de référence de production d'électricité, Paris, France, 1997, as quoted in: Nuclear Energy Agency "Background Note for the Policy Debate on the Thorium Fuel Cycle Briefing for the Delegates," OECD NEA publication NEA/SEN (2014)2, Oct. 7, 2014.

Table 5-1. **Comparison of Closed U/Pu fuel cycle costs versus Th fuel cycle costs**

Fuel Cycle Step	Closed U/Pu Fuel Cycle	Cost Fraction[65]	Thorium Fuel Cycle	Qualitative Cost Comparison for Th versus U/Pu only fuel cycle
Mining	U Mining	24.6%	Th Mining	Very low (a)
Conversion	U Conversion	3.3%	N/A (b)	Some U conversion needed initially (b)
Enrichment	U Enrichment	21.3%	N/A (b)	Some U enrichment needed initially (b)
Fabrication	U/Pu fuel assembly fabrication	16.4%	Thorium fresh and/ or recycled fuel fabrication	Once-through Th/LEU slightly higher (c) Once-through Th/Pu same (d) Closed Th cycle with recycled U-233, significantly higher (c)(e)
Interim storage, reprocessing, recycling	U/ Pu spent fuel	26.2%	Recycled Th fuel to recover U-233	Closed Th cycle with recycled U-233, significantly higher (e)
Final spent fuel and waste disposal	U/Pu spent fuel disposal	8.2%	Thorium spent fuel disposal	Approximately the same cost (f)
Cost Fraction		100%		Potentially lower costs overall

a. Direct thorium mining would not be needed for many decades since thorium could be extracted together with other marketable materials (such as REEs or titanium) as a byproduct. The price for mining and recovering thorium would probably be much lower than that of mining uranium, especially as exploitable thorium deposits are available in open air monazite mines, which facilitates the recovery of REEs, other minerals besides thorium.

b. The conversion and enrichment steps are not applicable for a closed thorium cycle in equilibrium. But initial thorium cores will require fissile LEU transition fuel. The transition thorium fuel cycle would require significantly larger amounts of natural uranium and separative work units (SWU) than for the standard uranium cycle for the same energy output, dependent on reactor type, burn-up, and fuel management. For thorium-based cycles, the cost associated with using recycled fissile material (plutonium or U-233) heavily depends on the back end of the chosen fuel cycle.

c. When considering the fabrication of fresh and/or recycled fuel fabrication of thorium-based fuels, it is necessary to distinguish the type of fissile “seed” driver fuel chosen for the fertile thorium fuel.

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[65] Ministère de l’Économie, des Finances et de l’Industrie (1997), Coûts de référence de production d’électricité, Paris, France, 1997, as quoted in: Nuclear Energy Agency “Background Note for the Policy Debate on the Thorium Fuel Cycle Briefing for the Delegates,” OECD NEA publication NEA/SEN (2014)2, Oct. 7, 2014.

d. Both fertile thorium and fissile LEU is used in once-through thorium cycle, resulting in some additional costs compared to standard enriched uranium fuel fabrication, particularly for heterogeneous fuel management options where thorium and uranium are physically separated (e.g., Radkowsky designs).[66] Homogeneous thorium/uranium LWR fuel cycle studies have shown that these fuel cycles are not economically competitive over conventional uranium cycles with current fuel management strategies.[67]

e. If plutonium is used with thorium in once-through cycles, the processes should not be very different from those that are used today in the manufacture of (U, Pu) MOX fuel, and therefore the costs should be comparable.

f. If fissile U-233 is used for closing the thorium fuel cycle, radioactive daughter products of U-232 would require remote operations. Recycled Th fuel fabrication would incur significant additional costs. No technically and economically proven processes and equipment that have been developed and demonstrated for remotely operated, recycled Th fuel fabrication at a large industrial scale.[68]

g. High-level long-lived waste would require permanent disposal. No significant economic difference between uranium and thorium cycles would be seen, especially if it is assumed here that only residual waste from reprocessing would be disposed. Different thorium spent fuel decay characteristics may impact extremely long-term design conditions and reduce ultimate disposal costs. For example, ThO_2 is more chemically inert and does not oxidize like UO_2, which oxidizes easily to U_3O_8, and UO_3; therefore, long term interim storage and permanent disposal of spent ThO_2–based fuel in a repository would be simpler without the problem of oxidation. Furthermore, once through thorium versus uranium fuel cycles produce different disposal volumes, as shown in Figure 2 which compares the disposal volumes generated for one ton of thorium versus U-235 fuel utilization.

Thorium versus Uranium fuel cycle issues

The use of thorium fertile fuel cycle that complements the uranium/plutonium fuel cycle could improve the medium-term flexibility and the long-term sustainability of nuclear energy. Specifically, the following technical issues associated with introducing thorium into nuclear fuel cycles would need to be investigated further: (a) using thorium as a means of burning plutonium (and possibly other higher actinides) as an option for plutonium management, (b) using thorium-based fuels to achieve higher conversion rates in thermal or epithermal neutron

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[66] Radkowsky, Alvin, Alex Galperin, "The Nonproliferative Light Water Thorium Reactor: A New Approach to Light Water Reactor Core Technology," Nuclear Technology, Vol 124, December 1998, pp. 215-222.

[67] Joo, Hyung-Kook et al., "Economical Ways for Thorium-Based Fuel Utilization in Light Water Reactors", Proceedings of the Korean Nuclear Society Spring Meeting, Gyeongju, Korea, May 2003.

[68] Joo, Hyung-Kook et al., "Economical Ways for Thorium-Based Fuel Utilization in Light Water Reactors", Proceedings of the Korean Nuclear Society Spring Meeting, Gyeongju, Korea, May 2003.

energy reactor designs, with the goal of recovering fissile material from spent nuclear fuel, and (c) understanding thorium dioxide mechanical and chemical characteristics which may improve in-core performance thoria-based fuels versus current uranium fuel designs.

Development of new thorium-based fuels or new reactor concepts is a time- and resource-consuming process. Any thorium fuel design would require the use of uranium/plutonium fissile “driver” fuel until enough U-233 is produced by neutron irradiation to make the fertile thorium cycle self-sustaining. The key factor governing the rate at which U-233 could be produced from the introduction of Th/Pu or Th/U/Pu fuel is the amount of Pu available. The time to obtain a fully closed, self-sustaining thorium/U-233 system is determined by the amount of “seed” U or Pu fissile material used with thorium.

The development of a fully self-sustaining closed thorium/U-233 fuel cycle would also require the development of industrial-scale reprocessing capabilities to recover the U-233 from spent fuel along with fuel fabrication facilities to prepare the material for reuse. Major impediments to having a closed thorium fuel cycle include the following issues:

- The thorium extraction (THOREX) process has been only demonstrated in laboratory facilities but has yet to reach the maturity of the commercial plutonium uranium reduction extraction (PUREX) process. Alternative conceptual processes could be investigated but would take years to develop.
- A major challenge associated with recycling U-233 produced in irradiated thorium fuel is the presence of radioactive U-232. Remotely operated and highly shielded recycled thorium fuel fabrication processes would likely be needed, for which there are currently no proven equipment or methods at the industrial scale.
- Thorium fuel technologies may require significant R&D. Given the huge costs and the lack of clear economic incentives for using thorium fuels, versus uranium-only fuel, industrial development activities for thorium remain somewhat limited at this time. Any development of thorium fuels will need to be done in a systematic and synergetic manner within the existing uranium/plutonium fuel cycle.
- Advanced dedicated thorium/uranium breeder/burner reactor designs that may be able to utilize a closed thorium/U-233 fuel cycle are still in the early conceptual design study phase. Breeding U-233 from thorium in a thermal neutron spectrum reactor is slow and would require extensive reprocessing.
- MSRs may offer the prospect of using thorium fuels with online uranium extraction (U-233) and/or recovery and reuse systems; however, the design, development, licensing, and construction of such novel separation systems is a major, costly, and long-term undertaking. Such on-line uranium chemical separation systems could also lead to U-233 extraction creating proliferation issues.

In summary, a self-sustaining thorium/U-233 fuel cycle might result in: (a) a significant reduction of the radiotoxicity of the waste, (b) higher fuel utilization efficiency, (c) a closed fuel cycle that would not require uranium conversion or enrichment, and (d) no need for fast reactors to burn transuranic isotopes when compared to uranium/plutonium fuels. However, the benefits of a thorium fuel cycle are modest when considering the long transition time needed to establish a fully closed thorium-only equilibrium cycle. The substantial reduction in radiotoxic spent fuel inventory in the decay range of 1,000 to 10,000 years that would result from a full thorium/U-233 fuel cycle could be nevertheless an attractive feature over the long term.

Figure 5-1. Comparison of Thorium, Uranium, Plutonium Fuel Cycle Waste Radioactivity[69]

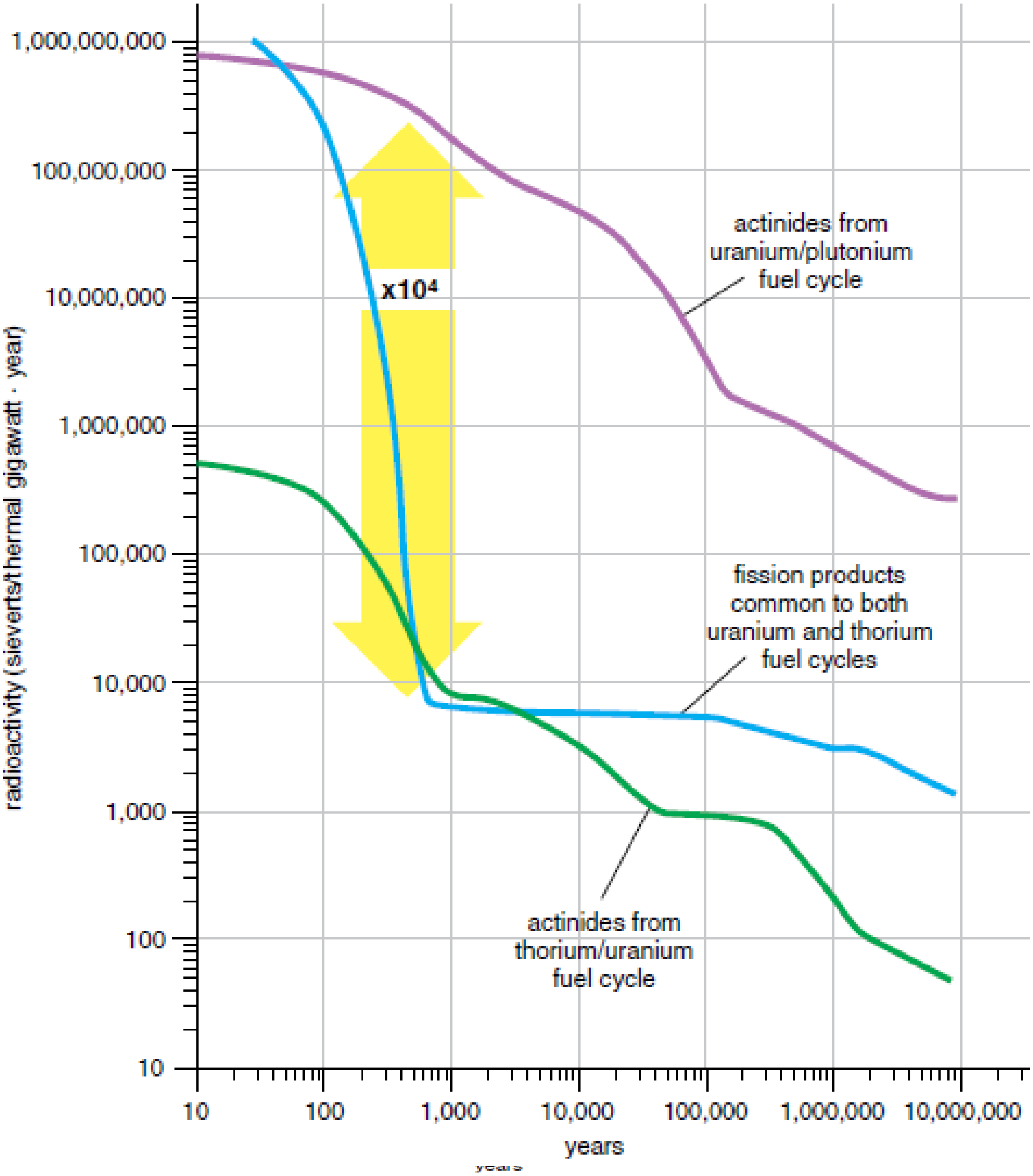
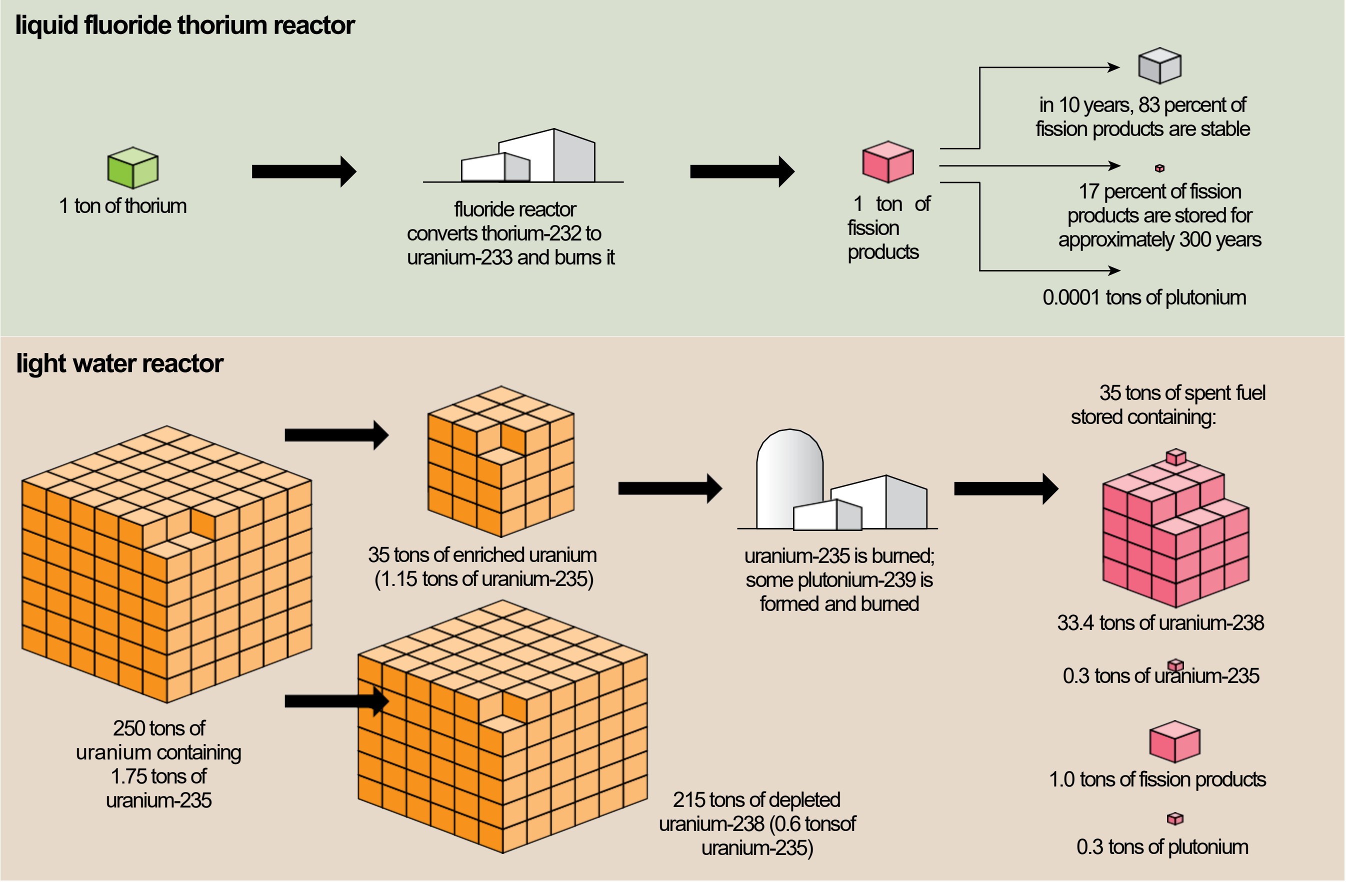


Figure 6. Switching to liquid fluoride thorium reactors would go a long way toward neutralizing the nuclear waste storage issue. The relatively small amount of waste produced in LFTRs requires a few hundred years of isolated storage versus the few hundred thousand years for the waste generated by the uranium/plutonium fuel cycle. Thorium- and uranium-fueled reactors produce essentially the same fission products, whose radiotoxicity is displayed in blue on this diagram of radiation dose versus time. The purple line is actinide waste from a light-water reactor, and the green line is actinide waste from a LFTR. After 300 years the radiotoxicity of the thorium fuel cycle waste is 10,000 times less than that of the uranium/plutonium fuel cycle waste. The LFTR scheme can also consume fissile material extracted from light-water reactor waste to start up thorium/uranium fuel generation.

Figure 5-2. Comparison of thorium and uranium once-through waste volumes for thorium liquid salt reactors versus LWRs.[70]



VI. Proliferation, Safeguards, Security, and Criticality Safety Issues

The United States explored the possibility of using Th-232 as a source to produce U-233 for nuclear weapons and concluded that it could be a very potent weapon when the first U-233 bomb was tested in 1955. Other U-233 bombs were tested but the presence of U-232 tended to "poison" the U-233 in two ways: (1) intense radiation from the U-232 made the weapon's material difficult to handle, and (2) the U-232 led to possible pre-detonation. Early methods for separating U-232 from the U-233 to get isotopically pure U-233 proved very difficult, especially

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[69] Hargraves, Robert and Moir, Ralph. "Liquid Fluoride Thorium Reactors: An old idea in nuclear power gets reexamined", American Scientist, Vol. 98, p. 304 (2010). Available at: http://www.ralphmoir.com/wp-content/uploads/2012/10/hargraves2010_2.pdf

[70] Hargraves, Robert and Moir, Ralph. "Liquid Fluoride Thorium Reactors: An old idea in nuclear power gets reexamined", American Scientist, Vol. 98, p. 304 (2010). Available at: http://www.ralphmoir.com/wp-content/uploads/2012/10/hargraves2010_2.pdf

extracting it from irradiating mixed Th/U/Pu fuel in LWRs, although modern laser separation techniques could facilitate that process.[71] According to Alvin Radkowsky, "a thorium reactor's plutonium production rate would be less than 2 percent of that of a standard (i.e., uranium-fueled) LWR reactor, and the plutonium's isotopic content would make it unsuitable for a nuclear detonation."[72]

Eventually, scientists were able to obtain U-233 by using a variety of chemical separation methods to extract protactinium 233 (Pa-233) from irradiated Th-232 fuel and allowing the Pa-233 to radioactively decay into isotopically pure U-233. The global nonproliferation regime has long recognized the inherent proliferation risk of protactinium separations in the thorium fuel cycle,[73,74,75] which has led to controls on thorium and uranium in the nuclear export control regimes and in U.S. law.[76] Protactinium separations and decay provide an easy pathway for obtaining highly attractive weapons-grade U-233 from thorium fuel cycles. The Nuclear Suppliers Group Part 1 Guidelines (the “Trigger List”) and the Zangger Committee control thorium as source material in section 1.1 and 2a, respectively, and U-233 as special fissionable material in section 1.2 and 2b, respectively. These controls require that states apply fundamental principles for safeguards and export controls before transferring these materials for peaceful purposes to any non-nuclear-weapon State.

In the United States, the export of thorium and U-233 are subject to the NRC’s export control regulations and the terms of an agreement for cooperation pursuant to Section 123, recognizing their inherent proliferation risk. Section 123 of the Atomic Energy Act requires that any such civil nuclear cooperation agreements include nine robust nonproliferation commitments from the international partner designed to ensure the highest level of safeguards, security, and nonproliferation controls.

Safeguarding commercial spent fuel reprocessing is complicated for any type of fuel cycle, and the thorium fuel cycle is no exception and not “intrinsically” proliferation resistant as some proponents have stated, nor does it necessarily have an increased proliferation resistance, given the proclivity of U-233 for nuclear weapons use. The importance of protactinium extraction chemistry in thorium fuel reprocessing needs to be recognized and addressed by measurement accountability safeguards technologies to reduce the chances that such a route

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[71] Ford, James and Schuller, C. Richard. Controlling threats to nuclear security a holistic model, United States Government Printing Office 1997, pp. 111–112.

[72] Martin, Richard. “Superfuel: Thorium, the Green Energy Source for the Future” Palgrave-Macmillan (2012).

[73] Uribe, Eva C. "Thorium power has a protactinium problem". Bulletin of the Atomic Scientists, August 6, 2018, available at: https://thebulletin.org/2018/08/thorium-power-has-a-protactinium-problem.

[74] Ashley, Stephen F., Geoffrey T. Parks, et. al, “Thorium fuel has risks,” Nature, vol. 492, December 6, 2012, pp. 31-33.

[75] Nelson, Andrew T., “Thorium: Not a near-term commercial nuclear fuel,” Bulletin of the Atomic Scientists, Volume 68, 2012, Issue 5, published online: 27 Nov. 27, 2015, pp. 33-44.

[76] Blix, Hans, “Thorium Nuclear Power and Non-proliferation,” in Thorium Energy for the World, https://link.springer.com/book/10.1007/978-3-319-26542-1, Springer, April 2006, pp. 147-150, and Thorium Energy Conference ThEC13, 2013, video available at: https://www.youtube.com/watch?v=F4m10Y0rWB&t=54s.

would be employed by would-be proliferators for acquiring weapons-usable U-233 from irradiated thorium fuel. As thorium fuel can be irradiated in commercial nuclear plants and produce U-233, it is a requirement of the international safeguards system of the IAEA that thorium and the entire thorium fuel cycle be safeguarded.

Effective safeguards, security, and export control regimes must detect: (a) the diversion or theft of fissile **materials** (U-233) from thorium-fueled reactor facilities, (b) the misuse of **facilities**, equipment and technology that handle irradiated thorium fuel from declared purposes, e.g., clandestine operations at fissile U-233 production and reprocessing facilities, and (c) the transfer of nuclear **technology** and skills to illicit purposes. Non-proliferation for a nuclear reactor or fuel system can be evaluated by assessing the relative effectiveness of diversion "barriers" designated as either as: (a) ***intrinsic*** material and technical features, or (b) ***extrinsic*** safeguards and institutional measures used to avoid proliferation.[77] The quality of fissile weapon material produced in uranium versus thorium fueled reactors can be compared by the amount of Pu discharged, and how much degradation is caused by spontaneous fissions and heat emission. Table 6-1 shows the proliferation resistance parameters for uranium versus thorium fuel in LWRs. Table 6-2 shows the materials barriers proliferation resistance capability of uranium versus thorium fueled LWRs.

Without appropriate international safeguards measures in place, any misuse of thorium fuel could go undetected. Current detection and intrinsic safeguards methods are focused on uranium and plutonium fuel cycles and may not be adequate for thorium fuel, particularly for reprocessing activities or monitoring chemical clean-up systems in liquid molten salt reactors. Different types of detection and safeguards methods for three thorium-based fuel cycles would be needed: (1) transition to thorium fuel for LWRs, (2) Th/U/Pu fuel in fast reactors using sodium coolant, and (3) thorium deployment in MSRs with liquid fuel. Development of specific thorium cycle detection, non-destructive assay techniques, and safeguards methods at high technology readiness levels will be required before thorium-fueled reactors are deployed.[78,79]

Significant gamma shielding and remote handling is required for any irradiated thorium fuel processing. The presence of U-232 in irradiated thorium fuel is often cited as providing self-protection against proliferation, because of its decay product gamma emissions, in particular, Thallium-208 emits a strong 2.6 MeV gamma ray when it decays. The level of proliferation resistance and self-protection that U-232 gamma emissions provide, however, depends on the proliferation threat scenario, i.e., on the capacity of proliferators to build or acquire shielded facilities and/or willingness to expose themselves or personnel to high radiation doses.

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[77] International Atomic Energy Agency, Thorium Fuel Cycle Potential Benefits and Challenges, IAEA- TECDOC 1450, Vienna, May 2005.

[78] Worrall, Louise G., Andrew Worrall, et al., "Safeguards Considerations for Thorium Fuel Cycles," Nuclear Technology, vol. 194, May 2016, pp. 281-293.

[79] Forsberg, C. W., S. N. Storch, L. C. Lewis, Uranium-233 Waste Definition: Disposal Options, Safeguards, Criticality Control and Arms Control, Oak Ridge National Laboratory, ORNL/TM-13591, July 7, 1998.

Several types of thorium fueled reactors enable the production of protactinium to generate U-233. Three intermediate protactinium isotopes are produced when thorium 232 is irradiated, namely Pa-231, Pa-232, and Pa-233, that eventually form U-233. Pa-233 can be chemically separated from thorium and decays into U-233 with a half-life of 27 days:

$$ {}^{232}_{90}\mathrm{Th} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{233}_{90}\mathrm{Th} \xrightarrow[22.3\ \mathrm{min}]{\beta^-} {}^{233}_{91}\mathrm{Pa} \xrightarrow[26.967\ \mathrm{d}]{\beta^-} {}^{233}_{92}\mathrm{U} $$

The half-lives of the three protactinium isotopes work in the favor of potential proliferators. Because Pa-232 decays faster than Pa-233, the isotopic purity of Pa-233 increases with time. If the protactinium is carefully separated from its uranium decay products a second time, this protactinium will decay into very pure weapons-usable U-233 over the next few months with a very low U-232 concentration.

Many chemical methods exist for the aqueous separation of protactinium from thorium and uranium oxides, including the commonly proposed THOREX process.[80,81,82] Once dissolved in acid, protactinium can simply be adsorbed onto glass or silica beads, exploiting the same chemical mechanism used by Meitner and Hahn to isolate protactinium from natural uranium a century ago.[83] Molten salt reactors with fissile and fertile fuel isotopes flowing in the salt coolant can be used to breed U-233 and extract protactinium by using chemical clean-up systems with resin beads and THOREX extraction chemistry.[84] Fixed thorium oxide “blanket” fuel assemblies irradiated on the periphery of a HWR can be aqueously reprocessed to extract irradiated protactinium and U-233. Many HWRs include continuous refueling operations, which means that irradiated thorium can be removed quickly and often, without shutting the reactor down. The irradiated thorium “blanket” radioactivity would be lower than the main core, so blanket fuel could be reprocessed immediately. Reprocessing of irradiated thorium fuel in India’s civilian and military HWRs creates unique safeguard challenges since India is not a member of the Nuclear Non-Proliferation Treaty. India has abundant thorium resources and is highly motivated to develop thorium reactors that can breed U-233. India operates the only reactor fueled by U-233, the Kalpakkam Mini reactor (better known as KAMINI).[85]

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[80] Achuthan, P.V., Ramanujam, A. (2013). Aqueous Reprocessing by THOREX Process. In: Das, D., Bharadwaj, S. (eds) Thoria-based Nuclear Fuels. Green Energy and Technology. Springer, London. https://doi.org/10.1007/978-1-4471-5589-8_7; Available at: https://link.springer.com/chapter/10.1007/978-1-4471-5589-8_7

[81] International Atomic Energy Agency, Thorium Fuel Cycle Potential Benefits and Challenges, IAEA- TECDOC 1450, Vienna, May 2005.

[82] Orth, D. A., “Savannah River Plant Thorium Processing Experience,” Nuclear Technology, Vol. 43, No.1, April 1979, pp. 63-74.

[83] Uribe, Eva, “Protactinium Production in Leading Thorium Fuel Cycles” Nuclear Science and Security Consortium Alumni Talk Series, University of California Berkeley, April 9, 2021. Video available at: https://nssc.berkeley.edu/events-and-programs/webinar-series/nssc-alumni-speaker-series/eva-uribe/

[84] W. R. Grimes, W. R., “Molten-Salt Reactor Chemistry,’ Nuclear Applications and Technology, vol. 8, February 1970, pp.137-155.

[85] Uribe, Eva C. "Thorium power has a protactinium problem". Bulletin of the Atomic Scientists, August 6, 2018, available at: https://thebulletin.org/2018/08/thorium-power-has-a-protactinium-problem.

Thorium fuel cycles produce weapons-usable U-233, so natural or depleted uranium (U-235 and U-238) could be added to “denature” the thorium fuel to make it difficult to separate out U-233 produced during irradiation from the other existing uranium isotopes during reprocessing.[86] In contrast to reactors fueled only with uranium where there is no natural means to “denature” the resulting plutonium isotopes, adding U-235 and U-238 to unirradiated thorium fuel produces an effective deterrent for separating U-233 from irradiated thorium. Furthermore, adding some natural or depleted uranium to thorium fuel improves safeguards detectability since it produces a unique U-232 radiation signature and higher spontaneous neutron emissions from U-238.[87] Denaturing U-233 by adding U-238 would also assist in lowering the proliferation risk, but this approach would offset the benefits of reduced plutonium production.

Thorium-based fuel cycles require fissile containing driver fuels, using either depleted, natural or low-enriched uranium (LEU) enriched up to 20 weight percent U-235, or plutonium and causes additional proliferation concerns. Handling irradiated thorium fuel safely involves special attention, particularly for the U-233 present. U-233 has a smaller critical mass than does either U-235 or Pu-239 and has other nuclear properties that are also significantly different from other fissile isotopes, so that U-233 has unique criticality safety processing and disposal issues. To avoid U-233 nuclear criticality issues, it was found that one part U-233 needs to be diluted with 188 parts by weight of DU (0.2 weight percent U-235), to ensure subcriticality in water and in dry conditions.[88] Thus, a relatively small amount of natural (or enriched) uranium can be added to thorium in order to dilute the generated U-233 below the proliferation level of 12 percent, thus creating an effective barrier to diversion of U-233.[89] More depleted or natural uranium would be required if other fissile uranium or plutonium isotopes are present, so that detailed criticality safety analysis would be required to ensure nuclear safety during fuel fabrication, reprocessing and disposal activities.

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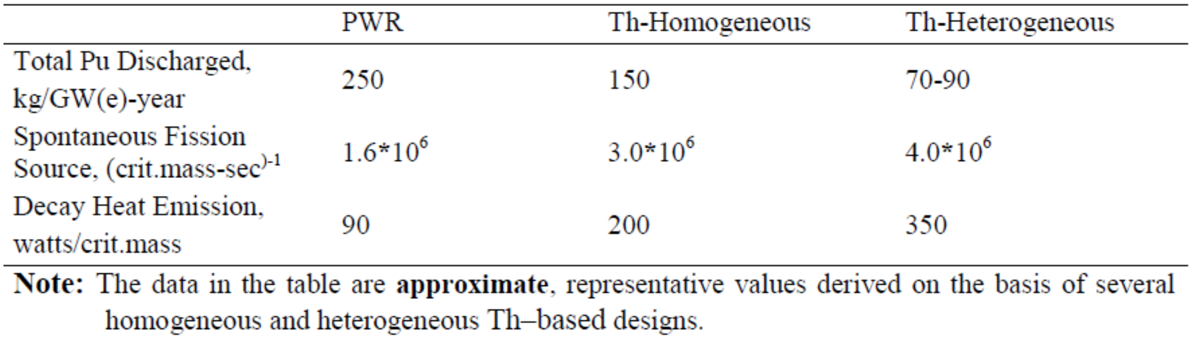
[86] Sege, Carol A., Saul Strauch, Ronald P. Omberg, Irving Spiewak, “The Denatured Thorium Cycle—An Overview,” Nuclear Technology, Vol. 42, No. 2, February,1979, pp.144-149.

[87] Sege, Carol A., Saul Strauch, Ronald P. Omberg, Irving Spiewak, “The Denatured Thorium Cycle—An Overview,” Nuclear Technology, Vol. 42, No. 2, February,1979, pp.144-149.

[88] Forsberg, C. W., C. M. Hopper, et al, “Definition of Weapons-Usable Uranium-233,” Oak Ridge National Laboratory, ORNL/TM-13517, March 1998.

[89] Elam, K. R, C. W. Forsberg, et al, “Isotopic Dilution Requirements for U-233 Criticality Safety in Processing and Disposal Facilities,” Oak Ridge National Laboratory, ORNL/TM-13524, Nov. 1997.

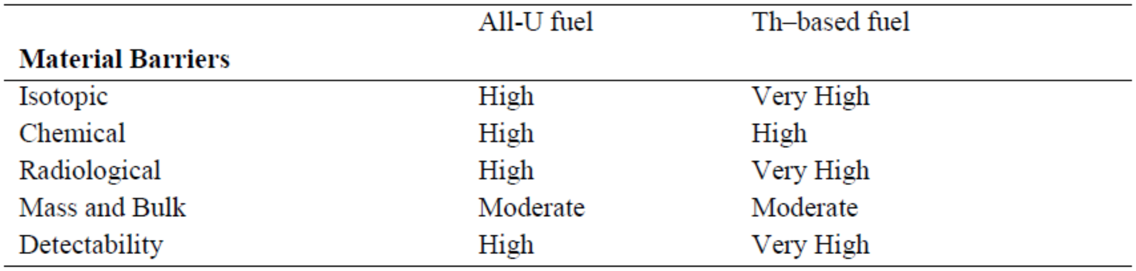
Table 6-1. Proliferation resistance parameters for uranium versus thorium fuel[90]



	PWR	Th-Homogeneous	Th-Heterogeneous
Total Pu Discharged, kg/GW(e)-year	250	150	70-90
Spontaneous Fission Source, (crit.mass-sec)$^{-1}$	$1.6*10^6$	$3.0*10^6$	$4.0*10^6$
Decay Heat Emission, watts/crit.mass	90	200	350

Note: The data in the table are **approximate**, representative values derived on the basis of several homogeneous and heterogeneous Th–based designs.

Table 6-2. Relative material barriers proliferation resistance capability of uranium versus thorium (heterogeneous seed blanket) fueled LWRs[91]



Material Barriers	All-U fuel	Th–based fuel
Isotopic	High	Very High
Chemical	High	High
Radiological	High	Very High
Mass and Bulk	Moderate	Moderate
Detectability	High	Very High

Reduction of U-233 inventories at ORNL

The DOE inventory of U-233 at ORNL is currently being down-blended for final disposition. Several stakeholders have suggested that DOE halt the disposition of U-233 inventories stored in Building 3019A at ORNL because they consider U-233 a national asset. In correspondence with Congress in 2021, NE responded to requests for additional information on alternatives for this U-233, expressing the view that DOE can achieve its mission to advance nuclear power to meet the Nation's energy, environmental, and national security needs without having a domestic inventory of U-233.[92] Currently, DOE's Office of Environmental Management (EM) manages the U-233 disposition program at ORNL, as part of the ORNL cleanup activities. EM has received regular appropriations from Congress to continue the disposition program and has contracted with Isotek to provide for disposition of the U-233. In turn, Isotek has a separate

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[90] International Atomic Energy Agency, Thorium Fuel Cycle Potential Benefits and Challenges, IAEA- TECDOC 1450, Vienna, May 2005.

[91] International Atomic Energy Agency, Thorium Fuel Cycle Potential Benefits and Challenges, IAEA- TECDOC 1450, Vienna, May 2005.

[92] Huff, Kathryn, Acting Assistant Secretary for Nuclear Energy, Letters to Congress in response to a December 2, 2020, letter to the U.S. Department of Energy (DOE) signed by fifteen members of Congress, regarding DOE's plans for the U-233 stored at the Oak Ridge National Laboratory (ORNL) and the thorium fuel cycle, dated September 14, 2021.

but related agreement with TerraPower that makes the byproduct of the U-233 disposition processing available as a medical isotope. The continuation of this agreement enables the production of vital material for targeted alpha therapy, which is a form of cancer treatment. DOE performed a preliminary assessment of U-233 shipment and possible storage options at INL and associated costs in November 2019. This preliminary assessment indicated that, should a private Thorium reactor developer express any interest in retaining the U-233 inventory for up to 5 years, it could cost up to $500 million. This cost estimate was a preliminary rough order of magnitude because no thorium reactor developer has approach DOE with a specific plan or proposal on how to manage the inventory of U-233.

The 2008 DOE Inspector General Report states: "Although other means of producing these medical isotopes are currently under investigation by the research community, it is not yet known whether any of these will come to fruition. The facilities that originally produced this material have all been closed and decommissioned. To produce uranium-233 using existing facilities, such as the Idaho National Laboratory's Advanced Test Reactor, program officials indicated that it would take approximately 1,000 years to replace the 320 kg of uranium-233 stored at Idaho. Another alternative is to produce the actinium-225 using accelerators or reactors; however, this requires chemical processing and/or separation steps that are yet to be determined. The current cost estimate to dispose of Idaho's inventory of uranium-233 is approximately $5 million. Alternatively, the current cost to store U-233 is approximately $60,000 per year. However, the maintenance and storage costs of uranium-233 will grow over time because of the radioactive decay process, so the material becomes increasingly more difficult to manage."[93]

VII. Thorium Fuel Licensing Issues and Regulatory Requirements

The development of new regulatory information and licensing changes required for any thorium-fueled reactor deployment will be very resource- and time-consuming. Fuel and reactor vendors may have many hurdles to overcome to obtain the experimental data needed to be able to have their specific designs licensed by the NRC. The NRC will need fundamental irradiation experimental data, post-irradiation examination information, and transient fuel performance experience to be able to license and regulate specific thorium fuel and reactor designs.

The most likely near-term application of thorium is in currently operating U.S. LWRs or in Generation IV LWRs, where fuel designs would : (a) use homogeneously mixed thorium with uranium (UO_2 + ThO_2) fuel pins, (b) add separate fertile thorium (ThO_2) fuel pins to LWR UO_2 fuel assemblies, or (c) use mixed plutonium and thorium (PuO_2 + ThO_2) fuel pins in LWR UO_2 fuel assemblies. The addition of thorium to currently operating or future LWRs would result in

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[93] U.S. Department of Energy, Office of Inspector General, Office of Audit Services, "Special Report: Meeting Medical and Research Needs for Isotopes Derived from Uranium-233," DOE/IG-0795, May 2008.

several different phenomenological impacts on the nuclear fuel. Thorium and its irradiation products have nuclear characteristics that are very different from those of uranium. In addition, ThO_2, alone or mixed with UO_2 fuel, leads to different chemical and physical properties of the fuel that result in key changes in reactor safety-related parameters. Other thorium-fueled non-LWR Generation IV designs may also have significant differences when compared to their uranium-only fueled designs that must be considered.[94]

Those phenomena associated with thorium fuel that are different when compared to typical UO_2 fuel include melting temperature, fission gas release, decay heat, and safety performance parameters (e.g., reactivity coefficients). Thorium deployment would involve new fuel designs, new operating limits (e.g., rod burnup, power ramp rates, and peak power), and different fuel fabrication details and spent fuel characteristics that would require NRC scrutiny. The NRC would likely need to conduct a thorough review of thorium-based fuels for LWRs to verify that new or existing design-basis limits, analytical models, and evaluation methods are applicable for the specific design for normal operation, anticipated operating transients, and postulated accidents. The NRC would also likely need to evaluate historical and current thorium operating experience, review existing and new experimental test results, perform benchmark comparisons, and develop detailed new methods, including fuel performance codes, and use other information for its safety reviews of thorium fuel and reactor vendors' licensing submittals. Some of the relevant thorium experience is decades old (e.g., Indian Point 1, Shippingport, Peach Bottom 1, Fort St. Vrain) and new R&D data would need to be obtained as part of NRC's updated thorium fuel regulations.[95]

The NRC published NUREG-7176 to give extensive information about what regulatory and licensing issues must be addressed for all aspects of LWR thorium fuel utilization including in-core performance, safety analysis document changes, spent fuel issues, and provided detailed qualitative and quantitative assessments of thorium fuel licensing parameters.[96] NUREG-7176 carefully addresses each aspect of the NUREG-800 Safety Analysis Report review process for changes that would be needed to deploy thorium fuel in LWRs such as fuel performance, thermal-hydraulics, reactor core control systems, operating technical specifications, radioactive source terms, spent fuel handling, etc. More information is provided about thorium fuel design and reactor design impacts in the appendices[97] and specific examples showing the differences between uranium only and uranium-thorium reactor physics calculations are given to show the complexity of thorium fuel issues.

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[94] Nuclear Energy Agency, "Background Note for the Policy Debate on the Thorium Fuel Cycle Briefing for the Delegates," OECD NEA/SEN (2014)2, Oct. 7, 2014.

[95] Nuclear Energy Agency, "Background Note for the Policy Debate on the Thorium Fuel Cycle Briefing for the Delegates," OECD NEA/SEN (2014)2, Oct. 7, 2014.

[96] Ade, Brian et al., (2014), Safety and Regulatory Issues of the Thorium Fuel Cycle, NUREG/CR-7176, U.S. NRC Publications, Washington, DC.

[97] Ade, Brian et al., (2014), Safety and Regulatory Issues of the Thorium Fuel Cycle, NUREG/CR-7176, U.S. NRC Publications, Washington, DC.

The NRC has emphasized that thorium's "…fundamental nuclear properties have impacts on a number of key areas related to reactor and safety analyses, including steady state and transient performance, fuel handling and management (fresh and irradiated), reactor operations, and waste management. The uncertainties on these data and the resulting impact on key safety parameters need to be fully evaluated." [98] The NRC's regulatory and evaluation processes would likely need to be developed specifically for each type of thorium-fueled reactor concept, for the thorium infrastructure changes, shipping, fuel fabrication, in-reactor fuel performance and safety analyses issues, spent fuel handling and storage.

Rather than describe the multitude of thorium fuel design parameters that the NRC must evaluate for licensing any thorium-fueled reactor,[99] only some of the most important licensing aspects are delineated below in terms of what must be done by the reactor fuel vendor, utility, and the R&D community:

- Transient fuel testing of irradiated thorium fuel will be needed to establish operating margins and fuel failure characteristics. Irradiation of prototypical thorium fuel in the INL ATR and testing in the INL Transient Reactor Test Facility (TREAT) may be needed to determine thorium fuel performance.

- Nuclear code data such as cross sections, radioactive decay, neutronics data needed for computer codes (e.g., radiation transport, depletion, neutron kinetics) are available for thorium but have not been as extensively validated as corresponding data for uranium. This is especially important not only for Th-232 and U-233 but also for the irradiation products of thorium, which include hard gamma emitters important to radioactive waste and radiation protection. Moreover, the data typically used to validate nuclear data, software, and methods, such as critical experiments usually performed at DOE labs, are lacking for thorium.

- Because of a lack of experiential knowledge of using thorium in modern LWRs, the uncertainties would be greater than for LWRs using UO_2-only fuels. Thorium-bearing LWR fuel may have larger uncertainties that would impact operating margins in the reactor, especially in terms of technical specification limits. The fuel vendors and licensees would need to address these uncertainties with experiments, computer code validations, etc., to reduce uncertainties and answer NRC questions.

- The radiological dose associated with radionuclide releases (i.e., source terms) during severe accidents depends on the ability of fuel to retain fission product gases. Current research suggests that thorium fuels may have higher melting temperatures and could

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[98] Ade, Brian et al., (2014), Safety and Regulatory Issues of the Thorium Fuel Cycle, NUREG/CR-7176, U.S. NRC Publications, Washington, DC.

[99] Ade, Brian et al., (2014), Safety and Regulatory Issues of the Thorium Fuel Cycle, NUREG/CR-7176, U.S. NRC Publications, Washington, DC.

retain fission gases longer than uranium-based fuels, but these characteristics would need to be validated through new experiments for the specific fuel design. The specific fission products and actinides produced during irradiation, radionuclide inventories, radiotoxicity, and decay heat characteristics of thorium fuels are different than from uranium-only fuels and must be evaluated by the NRC in licensing reviews.

- Reactor core physics conditions in the thorium-fueled may be very different than uranium-only fueled cores. Peak power locations, power peaking in radial blanket regions, local inside pin power distributions, pellet rim effects with the increase of fissile isotopes in thorium fuel will differ from uranium fuel and depend on the entire core design. Core axial and radial power distributions important for determining peak power conditions will determine the fuel limiting conditions. The different fission product and actinide concentration levels that will accumulate in thorium fuel could also potentially change the reactivity characteristics of the core and the neutron absorption of burnable absorbers, soluble poisons, controls rods, and other reactivity control mechanisms. Core physics analyses tools used by the fuel vendor and utilities will have to be able to predict operating and accident conditions based on the specific thorium and uranium fuel configuration and be able to determine the fuel isotopic burnup concentrations with fidelity.

- The different irradiation characteristics, depleted fuel isotopes, fuel performance, etc. in thorium fuel would change the safety parameters (i.e., reactivity coefficients) depending on the specific thorium core design used. The buildup of U-233 in fertile and fissile fuel assemblies/pins, size of the blanket region, and changes in fissile core content may alter the stability of the core and induce power oscillations during particular anticipated operational transients or accident conditions. Little data exist regarding core stability for thorium fueled reactors, but specific experiments, computer code models would need to be developed to determine whether such power oscillations exceed acceptable thorium fuel design limits.

- The addition of thorium to the core may also impact characteristics after the reactor is shut down. The U-233 produced from the decay of Pa-233 (half-life of 27 days) could impact refueling operations and intermediate spent fuel pool storage. Criticality safety computer tools will have to be able to predict U-233 production for out-of-core conditions. Plant refueling and fuel storage procedures will need to account for the increase in fissile U-233 that accumulates within the first months after reactor discharge.

- Some LWR thorium fuel designs have very different configurations than those in current LWRs, including very tight-pitch lattice designs that could significantly impact the hydraulic behavior for the fuel assemblies. The thorium fuel core designs may have an impact on critical heat flux and critical power ratio , fuel pellet densification, rod bowing, and power peaking locations, especially if the thorium blanket region fuel or heterogeneous thorium/uranium fuel assembly's configuration is different than the uranium-only fuel assembly in the same LWR core. Fuel pin physics and thermal-hydraulic (T/H) issues must be accounted for especially in terms of uncertainty, mixed assembly types, and T/H flow correlations.

- Specialized computer simulation codes that can model the complex fuel flowing in salt coolant MSRs or DMSRs and that can predict the isotopic concentrations, fuel movement, burnup, and conversion of the fissile and fertile fuel over the reactor lifetime may need to be developed by reactor vendors and require actual experimental data to benchmark their models. Removal of fission product species in the online chemical cleanup systems will need to be modelled as well. Novel computer simulation models will be required for operational conditions and accident analyses.

Licensing evaluations by the NRC would likely require not only specific thorium fuel performance data but also reactor-specific information in terms of regulatory guidance, licensing requirements, and data. Each reactor type has unique aspects for thorium fuel utilization.

Once-Through Thorium Cycle in LWRs with Enriched Uranium

Using thorium in a once-through fuel cycle in a reactor would require initial core fuel assemblies of enriched uranium with or without plutonium in MOX fuel to ensure criticality and desired irradiation cycle length for power production. In order to use thorium in LWRs, the uranium fuel must be more highly enriched than in a conventional UOX fuel fueled, e.g., 10 percent–20 percent U-235 instead of up to 5 percent in a PWR with standard uranium fuel because of the neutron-absorbing characteristics of thorium. These changes would require major modifications to the existing fresh fuel infrastructure (e.g., fabrication, shipping casks, etc.) to address the higher enrichments and the related criticality issues, in addition to any licensing issues associated directly with the use of thorium.

Additional NRC licensing guidance, regulations, and review of amendments to plant operating technical specification limits, procedures, and spent fuel handling would likely be needed.

The addition of thorium to currently operating LWRs would result in a number of different phenomenological impacts since thorium and its irradiation products have nuclear characteristics different from those for uranium. ThO_2 fuel, alone or mixed with UO_2 fuel, leads to different chemical and physical properties that impact reactor safety-related issues because they impact in-core safety parameters (e.g., power peaking, control rod worth, reactivity coefficients, and critical boron concentrations). Waste storage and transportation conditions (e.g., depleted fuel isotopic concentrations, decay heat, and radiological source terms) would be impacted by having thorium in the spent fuel.

Once-Through Thorium Cycle in High-Temperature Gas-Cooled Reactors with Enriched Uranium

HTRs have been associated with the use of thorium as a means to reduce the need for uranium. Both Peach Bottom 1 and Fort St. Vrain have operated with thorium fertile material, and thorium use has been considered in advanced Generation IV HTR concepts. Thorium-bearing, TRISO-coated particles can be intermixed with uranium- fueled particles in the same fuel compacts or pebbles or in separate thorium-only fertile compacts or pebbles. Specific licensing regulations and guidance would need to be generated or updated to handle thorium fuel in HTR TRISO fuel in terms of TRISO fuel fabrication, shipping casks, etc., to address safety issues.

Once-Through Thorium Cycles in Fast Reactors

Traditional fast reactor designs, such as sodium-cooled reactors, can operate in a once-through fuel cycle using fissile uranium with a fertile thorium region blanket in a “breed and burn” mode. Some Gen IV thorium/uranium concepts envision operating without fuel shuffling or refueling during the full reactor lifetime, while other concepts would involve shuffling of the fuel bundles. The discharged irradiated blanket thorium fuel would be expected to contain a relatively large quantity of fissile material (i.e., U-233) that would need to be handled. Specific NRC licensing regulations and guidance would be needed to address particular thorium-related safety issues in these fast reactor designs.

Once-Through Thorium Cycle in Molten Salt Reactors

MSRs were originally developed as thermal spectrum breeder reactors with recycling and the denatured MSR (DMSR) concept was developed as an alternative to reduce proliferation risk by eliminating online chemical processing and to operate the DMSR as a once-through thorium/uranium system. The DMSR is initially loaded with fertile thorium with fissile LEU (U-235), and only fresh LEU is added during the reactor’s operation, so that there is sufficient U-238 and U-235 to dilute and denature the U-233 that is produced by neutron capture by thorium.[100] All fuel remains in the salt coolant but only the volatile gaseous fission products are removed from the salt, while all other actinides and fission products are not separated. NRC licensing regulations and guidance would have to be developed for MSR and DMSR designs. The NRC would have to have to develop specialized computer simulation codes that can model the complex molten salt fuel movement, burnup, and conversion of the fissile and fertile fuel over the lifetime of the MSR or DMSR operations. Experimental data to benchmark their MSR models would also be needed. New computer simulation tools would be required for modeling

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[100] Sege, Carol A., Saul Strauch, Ronald P. Omberg, Irving Spiewak, “The Denatured Thorium Cycle—An Overview,” Nuclear Technology, Vol. 42, No. 2, February,1979, pp.144-149.

accidents and transients in fuel-flowing-in-salt-coolant conditions. New spent fuel regulations would be needed for salt-coolant waste storage, transport, and disposal.[101]

Thorium/U-233 Recycle Fuel Cycle Options

As a fertile material, thorium generally requires recycling to increase its fuel utilization and to recover U-233. Reactor systems supporting thorium fuel cycles can operate as converters or breeders. Converters require additional fissile material to operate (e.g., U or Pu), but breeders would eventually be self-sufficient on thorium and U-233 alone. If the recycling method separates thorium from uranium in a THOREX[102] process, then this separated uranium typically has a high U-233 fissile content and therefore represents a proliferation risk; however, the production of U-232 along with U-233 provides some proliferation protection. Should thorium recovery and U-233 recycling be considered, then new NRC regulations, guidance, and proliferation resistance safeguard standards would have to be developed not only for the recycling process, but also for the U-233 bearing fuel fabrication, shipping, handling, and in-reactor safety issues.

VIII. Non-Nuclear Applications

Historical Non-Nuclear Uses of Thorium

While thorium was discovered in 1828, its first application dates only from 1885, when Austrian chemist Carl Auer von Welsbach invented the gas mantle, a portable source of light which produces light from the incandescence of thorium oxide when heated by burning gaseous fuels. The radiation exposure from thorium lantern mantles is not considered to have significant health impacts. Thorium in mantles, although still common, has been progressively replaced with yttrium since the late 1990s.

Most thorium applications use its dioxide (sometimes called "thoria" in the industry), rather than the metallic form. Thorium dioxide compound has a melting point of 3300° C (6000°F), the highest of all known natural oxides;[103] only a few substances have higher melting points. This characteristic helps the thorium dioxide remain solid in a flame, and it considerably increases the brightness of the flame; this is the main reason thorium was first used in gas lamp mantles. All substances emit energy (glow) at high temperatures, but the light emitted by thorium is nearly all in the visible spectrum, hence the brightness of thorium mantles. When heated in air, thorium dioxide emits intense blue light; the light becomes white when ThO_2 is

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[101] Nuclear Energy Agency, "Background Note for the Policy Debate on the Thorium Fuel Cycle Briefing for the Delegates," OECD NEA/SEN (2014)2, Oct. 7, 2014.

[102] Orth, D. A., "Savannah River Plant Thorium Processing Experience," Nuclear Technology, Vol. 43, No.1, April 1979, pp. 63-74.

[103] Stoll, W., "Thorium and Thorium Compounds," Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH, 2005, ISBN 978-3-527-31097-5.

mixed with its lighter homologue cerium dioxide (CeO_2, ceria) thus forming the basis for its previously common application in gas mantles.[104]

Many applications were subsequently found for thorium and its compounds, including ceramics, carbon arc lamps, heat-resistant crucibles, and as catalysts for industrial chemical reactions such as the oxidation of ammonia to nitric acid. Catalysts containing an alloy made with 10 percent thorium/90 percent platinum were used to oxidize ammonia to make nitric acid for chemical processes including petroleum cracking and sulfuric acid production. Later the thorium was replaced by a 5 percent rhodium/95 percent platinum alloy because of its better mechanical properties and greater durability.

During the production of incandescent filaments, recrystallisation of tungsten was significantly lowered by adding small amounts of thorium dioxide to the tungsten sintering powder to before drawing the filaments. A small addition of thorium to tungsten thermos-cathodes considerably reduced the temperature of the emitted electrons, producing longer-lived filaments. Since the 1920s, thoriated tungsten wires have been used in electronic tubes and in the cathodes and anticathodes of X-ray tubes and rectifiers. Thanks to the chemical reactivity of thorium with atmospheric oxygen and nitrogen, thorium was used as a “getter” to remove small amounts of gaseous impurities in the evacuated tubes. The introduction of transistors in the 1950s significantly diminished this use, but not entirely.

Thorotrast, a suspension containing radioactive thorium dioxide particles, was used as a radiocontrast agent in medical X-ray radiography starting in the 1930s until the 1950s. Thorotrast produced excellent images because of thorium’s high opacity to X-rays; however, the radioactive thorium was retained in the body for many years emitting harmful alpha radiation and caused latent cancers. Now Thorotrast is used only in micro-radiology research to stain neural tissue examination samples.

Non-nuclear uses of thorium have been in decline since the 1950s because of environmental and safety concerns stemming from the natural radioactivity of thorium and its decay products. Since thorium is naturally present in the environment, people are exposed to tiny amounts in air, food, and water. The amounts are usually very small and pose little health hazard. Although thorium oxide is the most popular additive because of its low cost, it has been phased out in favor of non-radioactive elements such as cerium, lanthanum, and zirconium for dopants.

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[104] Mitchell, Brian S., “An Introduction to Materials Engineering and Science for Chemical and Materials Engineers, Wiley, 2004, ISBN: 978-0-471-47335-0.

Current Non-Nuclear Uses of Thorium

Thorium is currently used in many high-temperature performance materials applications including the fabrication of fire brick and heat-resistant paint. Trace amounts of thorium are used in microwave applications for the filaments of magnetron tubes used to generate microwave frequencies in microwave ovens and radars. Thorium dioxide is found in heat-resistant ceramics, such as high-temperature laboratory crucibles, either as the primary ingredient or as an addition to zirconium dioxide. Thorium is also used for making superconducting magnets.[105]

Thorium alloy metals are used to produce high-temperature performance, high-strength, and creep-resistant materials.[106] Thoria-dispersed nickel is used in combustion engines and other equipment that must survive high-temperature conditions and remain creep-resistant. Thoria-doped nickel is also used for hydrogen trapping and preventing oxidation and corrosion Ni-Cr-Al alloys. Thoriated tungsten metal is not easily deformed because the high-fusion material thoria augments tungsten's high-temperature mechanical properties, and thorium helps stimulate the electron emissions or "thermions." Thus, thorium-tungsten alloys are now used in thermionic converters and electrodynamic tethers for electricity generation in space applications.

Thoriated magnesium or "Mag-Thor" alloys are used in various aerospace applications, aircraft engines, and several military applications. Mag-Thor is the common name for a range of magnesium alloys containing thorium that commonly contain trace elements such as manganese, zinc, or other metal combinations. Mag-Thor alloys have been used in strategic military applications such as supersonic drone and surface-to-air missile construction particularly in their ramjet components. This is because thoriated magnesium alloys are lightweight and have high strength and creep resistance up to 350°C.

Thorium is used coating tungsten wire in electrical equipment and for controlling the grain size of tungsten in electric lamps. It is used in filaments for modern light bulbs, such as metal-halide lamps and parabolic aluminized reflector (PAR) lamps. PAR lamps produce highly directional beams and are widely used in commercial, residential, and transportation illumination, including theatrical lighting, locomotive headlamps, aircraft landing lights, and residential and commercial recessed lights. Metal-halide lamps consist of a fused quartz arc tube with electrodes, an outer bulb, and a base that produces light by an electric arc through a gaseous mixture of vaporized mercury and metal halides (i.e., compounds of metals with bromine or iodine). Light is produced by the arc between the two thorium-doped tungsten electrodes that are sealed into each end of the arc tube when an AC voltage is applied to them through molybdenum foil seals fused in silica.

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[105] Thorium Energy Alliance website: https://thoriumenergyalliance.com/5-2-non-nuclear-thorium-uses/.

[106] Mitchell, Brian S., "An Introduction to Materials Engineering and Science for Chemical and Materials Engineers, Wiley, 2004, ISBN: 978-0-471-47335-0.

Thorium started to be incorporated in camera lenses during the 1950s - 1970s to improve the refractive index in glass and decrease dispersion. The health risk from using older camera lenses is low since the radiation dose from thoriated glass is approximately equal to dose from natural background. Thorium-doped glass can become yellow over time but can be returned to its clear state by exposing it to high levels of ultraviolet (UV) light. Thorium is still used to make high-end optical devices, such as high-quality camera and telescopic lenses, advanced scientific instruments, and commercial lighting equipment. Thorium tetrafluoride is still used as an anti-reflection material in multilayered optical coatings since it is uniquely transparent to electromagnetic waves having wavelengths in the range of 0.350–12 µm, a range that includes near UV, visible, and mid-infrared light. Replacements for thorium tetrafluoride, which have been under development since the 2010s which include lanthanum trifluoride, which is a transparent, high-refractive index material in the far UV range (100 nm - 200 nm). Thorium dioxide has since been replaced in optical applications by other rare-earth oxides, such as lanthanum since they provide similar effects and are not radioactive.

Thorium oxides are used in gas tungsten arc welding (GTAW), also known as tungsten inert gas (TIG) welding**,** to increase the high-temperature strength of the non-consumable tungsten electrodes (i.e., rods) and to improve arc stability. Thorium oxide alloy electrodes offer excellent arc performance thus making them popular as general-purpose electrodes. However, since thorium is slightly radioactive, inhaling the vapors and dust during TIG welding present health, disposal, and environmental risks. Thorium oxide alloy welding rods are slowly being replaced by other such as zirconium, cerium, and lanthanum.

Natural and irradiated thorium can be chemically purified to extract useful medical isotopes for diagnostic use and cancer therapy.[107] Radium-223 derived from proton-irradiated thorium is the first alpha-emitting isotope that obtained Food and Drug Administration approval for the treatment of various cancers, including bone, skin, prostate, and gynecologic cancers. Figure 8-1 shows the process for extracting radioactive radium and barium from proton-irradiated thorium, which is produced in accelerators. Daughter nuclides that produce alpha particles from thorium radioactive decay, such as lead-212, bismuth 213 and actinium 225, are also used in nuclear medicine for cancer therapy. Th-227, an alpha emitter with an 18.68-day half-life can be used in cancer treatments for targeted alpha therapies. Currently the domestically produced supply of actinium-255 and bismuth-233 is limited by the availability of the parent radionuclide, Th-229, which is derived from U-233 produced in nuclear reactors by irradiating natural Th-232. Appendix A Figure A-3 shows how actinium-255 and bismuth-233 can be produced from irradiating thorium and producing U-233, and through the radioactive decay chain.

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[107] DOE Office of Science, Nuclear Physics Office, "Thorium Source of Medical Isotopes" https://www.energy.gov/science/np/articles/thorium-source-multiple-medical-isotopes.

Energy Fuels recently announced a strategic alliance with RadTran to evaluate the recovery of thorium and potential radium medical isotopes for the emerging market for targeted alpha therapy cancer therapeutics.[108] Energy Fuels extracts and processes rare earth carbonates and uranium at its White Mesa Mill in Utah, which is currently the only licensed and operating conventional uranium mill existing in the U.S. The rare earth carbonate is extracted from natural monazite sands that also contain thorium and radium isotopes that can be extracted at a lower cost than the current medical isotope production methods.

Thorium radiometric dating is used along with carbon dating to date fossils, seabeds, and mountain ranges. Thorium-230/Th-232 dating methods can be used to date marine sediments. Th-230 has a half-life of about 80,000 years, which makes it suitable for dating sediments as old as 400,000 years. Because uranium compounds are soluble in seawater, while thorium compounds are quite insoluble, the thorium isotopes produced by the decay of uranium in seawater are readily precipitated and incorporated in sediments. Protactinium-231/Th-230 dating is used to date marine sediments as old as 175,000 years. Protactinium and thorium have very similar chemical properties and appear to be precipitated at the same rates in marine sediments. Pa-231 has a half-life of 32,500 years so using it with Th-230 constitutes a better radioactive dating method than using them separately because they do not need to have a uniform sedimentation rate through time but need only be precipitated in the same proportion. Very long-lived isotopes are difficult to use for dating young rocks because the extremely small amounts of daughter isotopes present are difficult to measure. Short half-life radioactive daughter isotopes present in uranium and thorium-decay chains exist in equilibrium amounts. But when a uranium-bearing mineral breaks down and dissolves out of the rocks or coral, the concentration of thorium daughter isotopes are disrupted; thus, uranium–thorium dating techniques determine a sample’s age by calculating the secular equilibrium amount of Th-230 present compared to the production rate of U-234, its parent isotope.

One isotope of thorium, Th-229 has a nuclear isomer (or metastable state) Th-229m, with a remarkably low excitation energy, recently measured to be 8.28 ± 0.17 eV. Laser spectroscopy of the Th-229 nucleus could be used to activate the low-energy transition for the development of a “nuclear clock” of extremely high accuracy.[109] Th-229m activation would use a nuclear shell transition rather than an atomic shell transition used in the most precise optical atomic clocks used today. For more than four decades nuclear physicists have targeted the identification and characterization of this elusive nuclear state (Th-229m), representing the lowest nuclear excitation in the whole landscape of known isotopes. In recent years considerable progress has been achieved on unveiling the properties of Th-229m including the precise measurement of its atomic decay parameters, half-life, and determination of its excitation energy. Development of an optical, laser-based control method for activating Th-229

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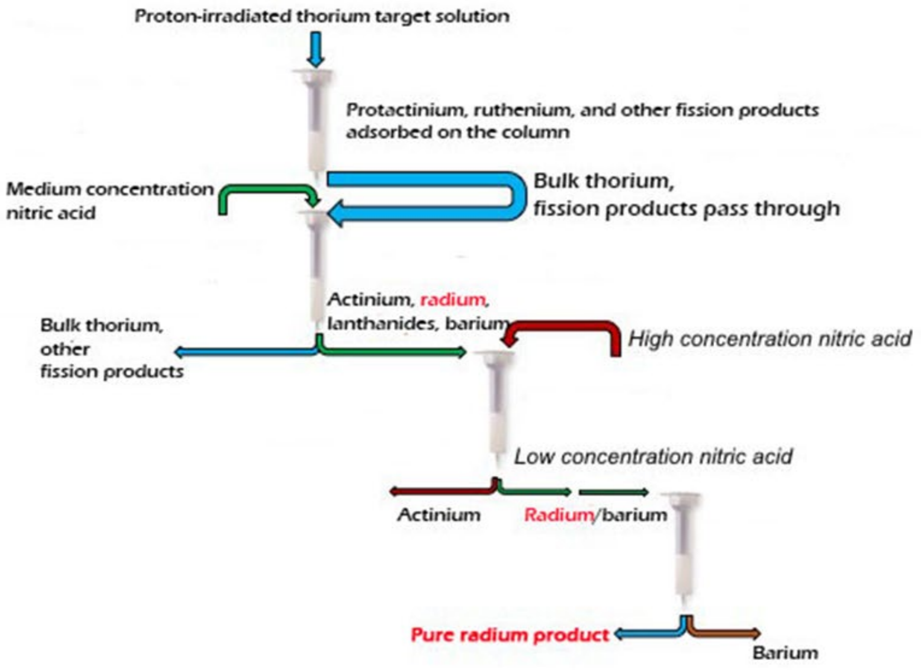
[108] Energy Fuels, “Energy Fuels investigates possible recovery of thorium, and radium,” Nuclear Engineering International, August 3, 2021. Available at: https://www.neimagazine.com/news/newsenergy-fuels-investigates-possible-recovery-of-thorium-and-radium-8962064/

[109] Thirolf, P. G., http://meetings.aps.org/Meeting/DAMOP21/Session/Q02.4. Meeting of the American Physical Society Division of Atomic, Molecular and Optical Physics. June 3, 2021.

into the Th-229m isomeric state could lead to an extremely precise nuclear frequency clock that could be used for earth positioning and geodesic calculations, seismic research, telecommunication satellite synchronization, and advanced physics research.

Figure 8-1. Radium and Barium Nuclear Medicine Extraction from Proton-Irradiated Thorium

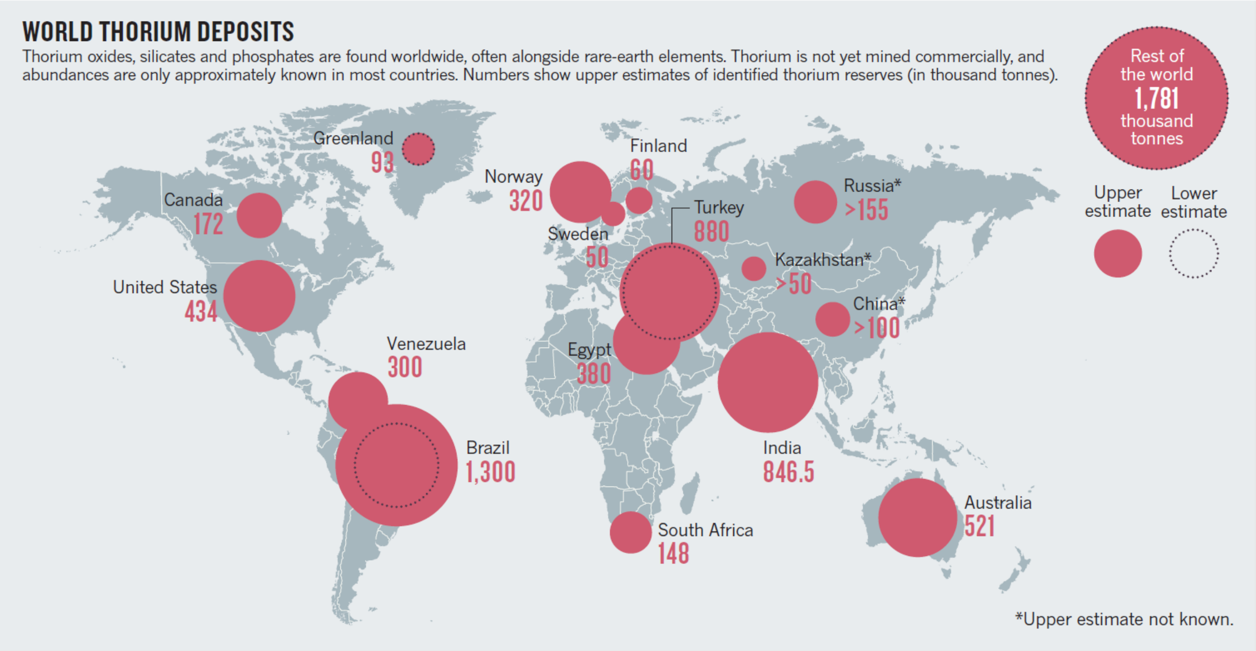


IX. Thorium and Rare Earth Materials Resources

Thorium is estimated to be over three times as abundant as uranium in the Earth's crust and is chiefly refined from monazite sands as a by-product of extracting REEs. Other sources such as thorite contain more thorium and could easily be used for production if the demand for thorium greatly increased. Thorium is mostly found with the rare earth phosphate mineral, monazite, which contains up to about 12 percent thorium phosphate, but usually contains 6–7 percent thorium on average.

World monazite resources are estimated to be about 12 million tons, two-thirds of which are in heavy mineral sands deposits on India’s south and east coasts. There are substantial estimated deposits in the U.S. and several other countries as shown in Figure 9-1. Appendix B provides more details about thorium resources and their locations. Low demand for thorium makes direct thorium mining not profitable,[110,111] and it is almost always extracted with REEs, which also may be by-products of production of other minerals, such as phosphates and titanium. About 7 million metric tons of titanium are recovered annually, so thorium by-product recovery from currently active titanium and phosphate mines could be an order of magnitude greater than estimated volumes of uranium currently used yearly by the world's entire nuclear reactor fleet.

Figure 9-1 World Thorium Deposits



WORLD THORIUM DEPOSITS

Thorium oxides, silicates and phosphates are found worldwide, often alongside rare-earth elements. Thorium is not yet mined commercially, and abundances are only approximately known in most countries. Numbers show upper estimates of identified thorium reserves (in thousand tonnes).

*Upper estimate not known.

SOURCE: URANIUM 2011: RESOURCES, PRODUCTION AND DEMAND (OECD NEA/IAEA; 2012).

Monazite is a good source of REEs but extracting REEs from monazites is not economical mainly because the radioactive byproduct thorium would have to be stored indefinitely. However, if thorium-fueled power plants were adopted on a large-scale, much of the world's thorium requirements could be supplied by using the separated thorium derived by extracting valuable REEs from refined monazites. There are different common species of monazite, depending on the relative amounts of the REEs. Cerium (Ce,La,Nd,Th)PO_4, the most common type of monazite, Samarium (Sm,Gd,Ce,Th)PO_4, and Praseodymium (Pr,Ce,Nd,Th)PO_4 forms of monazite contain thorium and other REE minerals. Cerium (Ce,La,Y,Th)PO_4 is a rare earth/thorium phosphate monazite material with 22 percent thorium and 14 percent REEs and yttrium. These various monazites could supply REEs such as cerium, dysprosium, erbium,

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[110] International Atomic Energy Agency, "Thorium-based Nuclear Fuel: Current Status and Perspectives," Proc. Technical Committee Meeting, Vienna, December 1985, IAEA -TECDOC-412, March 1987.

[111] Idaho National Laboratory, "Advanced Fuel Cycle Cost Basis Report: Module A2 Thorium Mining and Milling," DOE-NE Systems Analysis and Integration Campaign, Idaho Falls, 2021, INL/EXT-21-61493, Rev. 1.

europium, gadolinium, lanthanum lutetium, neodymium, praseodymium, samarium, terbium, thulium, ytterbium, and yttrium.[112,113] The REEs found in thorium bearing monazites are used in essential products including clean-energy production machinery such as solar panels, windmills, and hybrid cars. Detailed description of U.S. and global thorium resources and extensive information about REE availability, ore costs, and uses can be found in Appendix B and in the references.[114] Figure 9-2 shows the general availability of REEs and their applications.[115]

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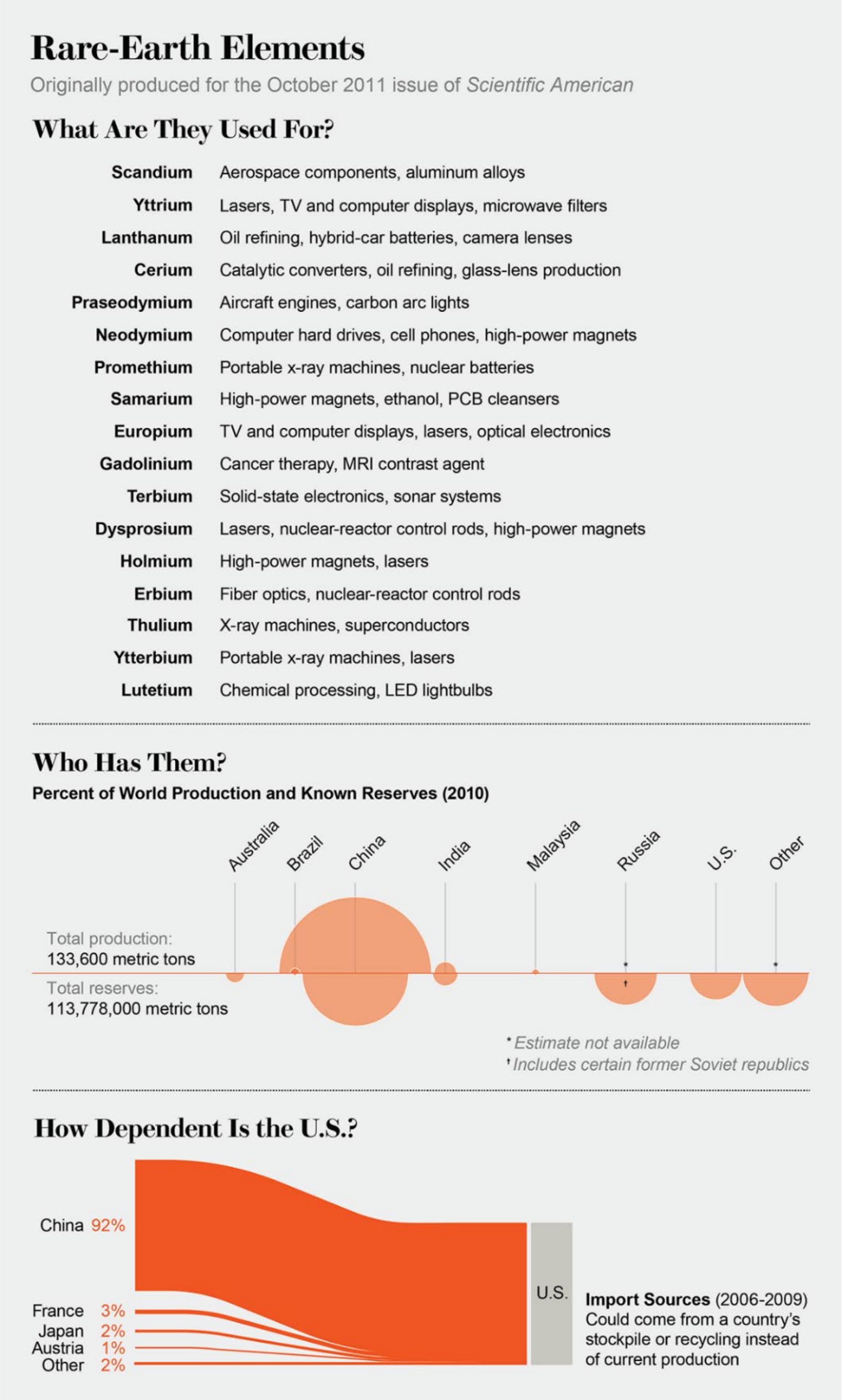
[112] Ragheb, Magdi, Lefteri Tsoukalas, "Global and USA Thorium and Rare Earth Elements Resources," Proc. 2nd Thorium Energy Alliance Conf., The Future Thorium Energy Economy, Mountain View, CA, March 29-30, 2010.

[113] Hsu, Jeremy, "Don't Panic about Rare Earth Elements," Scientific American, May 31, 2019. Available at: https://www.scientificamerican.com/article/dont-panic-about-rare-earth-elements/.

[114] Ragheb, M., "Thorium Resources in Rare Earth Elements," August 12, 2011, Available at scribd.com: https://www.scribd.com/document/105448071/Thorium-Resources-in-Rare-Earth-Elements-Ragheb-M-Aug-2011.

[115] Hsu, Jeremy, "Don't Panic about Rare Earth Elements," Scientific American, May 31, 2019. Available at: https://www.scientificamerican.com/article/dont-panic-about-rare-earth-elements/.

Figure 9-2. Rare-Earth Elements[116]



Rare-Earth Elements

Originally produced for the October 2011 issue of *Scientific American*

What Are They Used For?

Scandium	Aerospace components, aluminum alloys
Yttrium	Lasers, TV and computer displays, microwave filters
Lanthanum	Oil refining, hybrid-car batteries, camera lenses
Cerium	Catalytic converters, oil refining, glass-lens production
Praseodymium	Aircraft engines, carbon arc lights
Neodymium	Computer hard drives, cell phones, high-power magnets
Promethium	Portable x-ray machines, nuclear batteries
Samarium	High-power magnets, ethanol, PCB cleansers
Europium	TV and computer displays, lasers, optical electronics
Gadolinium	Cancer therapy, MRI contrast agent
Terbium	Solid-state electronics, sonar systems
Dysprosium	Lasers, nuclear-reactor control rods, high-power magnets
Holmium	High-power magnets, lasers
Erbium	Fiber optics, nuclear-reactor control rods
Thulium	X-ray machines, superconductors
Ytterbium	Portable x-ray machines, lasers
Lutetium	Chemical processing, LED lightbulbs

Who Has Them?

Percent of World Production and Known Reserves (2010)

*Estimate not available

†Includes certain former Soviet republics

How Dependent Is the U.S.?

Import Sources (2006-2009)
Could come from a country's stockpile or recycling instead of current production

Clean non-nuclear energy technologies require REEs for their deployment. Solar photovoltaic plants, wind farms and electric vehicles generally require more strategic metals and REEs to build than their fossil fuel-based counterparts. A typical electric car requires 6 times more mineral inputs (i.e., REEs and specialty metals) than a conventional fossil-burning car needs. An onshore wind plant requires 13 times more REEs and specialty mineral resources than a similarly sized gas-fired plant. Since 2010 the average amount of minerals needed for a new unit of power generation capacity has increased by 50 percent as the share of renewables in new investment has risen.[117]

The critical minerals needed for a transition to clean energy resources requires important minerals such as copper, lithium, nickel, cobalt, and REEs. Lithium, nickel, cobalt, manganese, and graphite are crucial to battery technology. REEs are essential for permanent magnets in wind turbines and electric vehicle motors, while copper is a fundamental metal needed for all electricity-related technologies. The International Energy Agency (IEA) estimates that if the world is to reach net zero energy goals by 2050, the overall demand for critical minerals, including REEs, will increase by a factor of six[118] for a range of clean energy technologies, including renewable energy, nuclear power, electricity networks, electric vehicles, battery storage and hydrogen technologies. The IEA estimates[119] nuclear power plant key mineral needs, based on data from the European Commission Joint Research Centre, to include chromium (2190 kg per MW), copper (1470 kg/MW), nickel (1300 kg/MW), hafnium (0.5 kg/MW) and yttrium (0.5 kg/MW), which could be obtained from extracting REEs from monazite mill tailings.

REEs must be purified to be used in modern applications. Similarly, highly purified thorium concentrations would be needed in nuclear reactor applications. In particular, concentrations of impurities with high neutron capture probabilities (i.e., cross-sections) must be very low. For example, gadolinium concentrations must be lower than one part per million by weight. Historically, industrial thorium extraction, production, and purification has relied on treatment with hot, concentrated sulfuric acid in cast iron vessels, followed by selective precipitation by dilution with water and relied on the specifics of the technique and the concentrate grain size. Many alternative processes have been proposed, but only one has proven effective economically: alkaline digestion with hot sodium hydroxide solution. This is more expensive than the original method but yields a higher purity of thorium; in particular, it removes phosphates from the concentrate. Thorium may then be separated by precipitating it as the phosphate at pH 1.3, since the rare earths do not precipitate until pH 2. Previously, repeated dissolution and recrystallisation was used to achieve high purity, but today, liquid solvent

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[116] IBID

[117] International Energy Agency (IEA), "The Role of Critical Minerals in Clean Energy Transitions," Report number, IEA, Paris, 2021. Available at: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

[118] International Energy Agency (IEA), "The Role of Critical Minerals in Clean Energy Transitions," Report number, IEA, Paris, 2021. Available at: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

[119] International Energy Agency (IEA), "The Role of Critical Minerals in Clean Energy Transitions," Report number, IEA, Paris, 2021. Available at: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

extraction procedures involving selective complexation of Th4+ are used.[120] For example, following alkaline digestion and the removal of the phosphates, the resulting complexes of thorium, uranium, and the REEs can be easily separated by employing tributyl phosphate extraction chemistry. Thus, titanium and phosphates can be removed from monazites, and the resulting mining "waste" tails can be chemically treated with modern solvent extraction methods (complexation) to separate thorium from the REEs.[121]

If ever needed in the distant future, direct dedicated thorium mining is generally easier than mining uranium. One of the advantages of direct thorium mining, compared to uranium mining, is that thorium can be extracted from open pit monazite deposits, the main source of thorium, which is easier than mining uranium-bearing ores. Management of thorium mine tailings is also simpler because of the much shorter half-life of one of its daughter products, radon-220 (55 seconds), compared to the equivalent daughter product of uranium, radon-222 (8 days). However, the radioactivity of the mined products is much higher for thorium than for uranium, because of the thorium decay chain product thallium-208, which emits 2.6 MeV gamma rays.

The overall abundance of thorium is not an issue for any short to medium term deployment of thorium-fueled nuclear power plants. If thorium-based fuel cycles were to be pursued worldwide, the quantities of thorium available as a by-product of the extraction of other minerals (rare earths, titanium, phosphates) would be able to provide enough quantities of thorium for its use in the nuclear industry for this purpose.[122] The extraction of REEs from existing phosphate monazite mining mill tailings would be better facilitated by the removal of thorium to reduce radioactivity levels during the REE recovery process. The thorium extracted could be safely and separately stored for fueling future nuclear reactors and for use in non-nuclear applications, such as high-temperature ceramics, melting tanks, catalysts, welding electrodes and metal alloys.

The only near-term economic benefit of considering future thorium fuel utilization may be that by removing and storing the naturally radioactive thorium that contaminates monazite wastes, valuable REEs can be safely extracted. REEs refined from mining waste streams would meet the industrial demands for essential rare earth materials in strategic industries, including advanced technologies, carbon-free energy production, transportation, manufacturing, and defense and security needs. But REEs and thorium are linked at the mineralogical, regulatory, and geopolitical level. U.S. NRC and international safety regulations pertaining to the radioactivity of natural thorium have contributed to market distortions related to REEs. The proliferation of regulations reflecting international standards regarding the definition of nuclear "Source

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[120] Ault, Timothy, Bradley Van Gosen, et al., Natural Thorium Resources and Recovery: Options and Impacts. Nuclear Technology, Vol. 194, No. 2, May 2016, pp. 136-151.

[121] Ault, Timothy, Bradley Van Gosen, et al., Natural Thorium Resources and Recovery: Options and Impacts. Nuclear Technology, Vol. 194, No. 2, May 2016, pp. 136-151.

[122] Ault, Timothy, Steven Krahn, Allen Croff, "Assessment of the Potential of By-Product Recovery of Thorium to Satisfy Demands of a Future Thorium Fuel Cycle," Nuclear Technology, Vol, 189, No. 2, February 2015, pp. 52-162.

Material" eliminated these high value REEs from the value chain for most of the world. Since the 1980s, refineries have no longer wanted to accept or accumulate thorium-bearing "tails" since laws governing the thorium-bearing monazite waste materials considered them to be nuclear "source materials", so mining and ore refining companies began down-blending the waste ore or dumping it into tailings lakes.[123]

The U.S. Congress has proposed in the past fifteen years several legislative bills and actions that would resolve the free market REE imbalance through the creation of a multi-national rare earth cooperatives and a "Thorium Storage, Energy & Industrial Products Corporation," and related entities in an attempt to have a reliable U.S. REE supply. The approach taken would have the costs for thorium removal from U.S. mining wastes and storing the thorium defrayed by the sales of REEs to domestic and foreign users, who would have a reliable U.S. supply chain instead of depending on Chinese REE imports. China's REE industrial policy does not include regulatory restrictions on REE mining and processing. The Chinese government provides direct and indirect investment support for REE related enterprises, including large scale state-sponsored research and development, so REEs can be produced very cheaply.

In September 2010, China stopped shipping REEs to Japan in response to a territorial dispute, and announced restrictions on export quotas to other countries.[124] China continues to control the world's supply of REEs and the resulting market concentration in China has caused severe economic dislocation and national security issues for the U.S., the European Union, Japan, Korea, and other nations.[125]

The NRC's regulations on unimportant quantities of source material exempt any person from its regulations in 10 CFR Part 40 and the requirements for a license set forth and the regulations set forth in parts 19, 20 and 21 in section 62 to the extent that such person receives, possesses or transfers rare earth metals and compounds, mixtures and products containing not more than 0.25 percent by weight thorium, uranium, or any combination of them. 10 CFR 40.13(c)(1)(vi). This exemption applies to rare earth metals and compounds, mixtures, and products from the only operating REE mining and processing facility in the U.S the Mountain Pass mine in California, which in 2020 supplied 15.8 percent of the world's rare-earth production. However, the primary ore of the Mountain Pass deposit has very low levels of thorium, but also lacks important recoverable heavy rare earths (Tb, Dy, Ho, Er, Tm, Yb, Lu, Sc) that would make the mine profitable. The Mountain Pass mine has changed ownership from Molycorp after its 2016

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[123] Kennedy, J. C., J. H. Kutsch, "Creating a Multi-National Development Platform: Thorium Energy & Rare Earth Value Chain," International Atomic Energy Agency URAM - Symposium on Uranium and Raw Materials for the Nuclear Fuel Cycle: Exploration, Mining, Production, Supply and Demand, Economics & Environmental Issues, IAEA Headquarters, Vienna Austria, June 23 – 27, 2014.

[124] Mills, Mark P., "Tech's Mineral Infrastructure--Time to Emulate China's Rare Earth Policies," Forbes Magazine, January 2, 2011. Available at: https://www.forbes.com/sites/markpmills/2011/01/01/techs-mineral-infrastructure-time-to-emulate-chinas-rare-earth-policies/?sh=34d7aa103b47

[125] Mamula, Ned, William Murray, "A renaissance to reverse U.S. strategic minerals imports: Dig, Baby, Dig," The Hill, October 23, 2017. Available at: https://thehill.com/opinion/energy-environment/356729-a-renaissance-to-reverse-us-strategic-minerals-imports-dig-baby#bottom-story-socials

bankruptcy when the bankrupt mine was sold to a Chinese-led business consortium MP Materials in June 2017 for $20 million.[126] Shenghe Resources Holding Co. Ltd, which is owned by the Chinese government has 8 percent ownership in MP Materials. After China doubled import duties on REE concentrates to 25 percent and restricted U.S. access to Chinese heavy REEs, as a result of the U.S.-China trade war, MP Materials stated in May 2019 it would start its partial U.S. processing by 2020, though full processing operations without Shenghe Resources will be delayed until 2022.[127]

In 2014, the "National Rare Earth Cooperative Act"[128,129] was designed to use REE resources within a federally chartered Rare Earth Cooperative and Thorium Corporation that would serve as a fully integrated supply chain for rare-earth materials. The cooperative would be owned and funded by multi-national corporations, defense contractors, sovereign nation agencies, sovereign wealth funds, end-user organizations and suppliers who would commit their capital. More importantly, the 2014 NRECA bill would have also created a federally chartered "Thorium Energy and Industrial Products Corporation" that will take all liability and physically hold and safely store all thorium and associated actinide liabilities from the Rare Earth Cooperative.

Senator Mark Rubio submitted a bill to the U.S. Senate in 2019 that would have established a thorium-bearing rare earth refinery cooperative that would serve to remove thorium that contaminates mining wastes so that REEs could be extracted and processed to meet U.S. rare earth materials needs.[130] The bill was identified as the "Rare Earth Cooperative 21st Century Manufacturing Act" or "RE-Coop 21st Century Manufacturing Act" and specifically noted that the "regulations regarding thorium represent a barrier to the development of a rare earth industry that is based in the U.S." The creation of a REE cooperative would meet strategic national interests including serving U.S. national security needs for procurement of weapons systems equipment and the needs of U.S. industrial manufacturers and achieve environmental safety and cleanup goals. If Senate bill 2019 S. 2093 or its update were re-introduced in Congress, it could support and advance domestic REE refining and ensure safe storage of thorium in anticipation of the potential future of thorium for nuclear energy production and

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[126] Mamula, Ned, William Murray, "A renaissance to reverse U.S. strategic minerals imports: Dig, Baby, Dig," The Hill, October 23, 2017. Available at: https://thehill.com/opinion/energy-environment/356729-a-renaissance-to-reverse-us-strategic-minerals-imports-dig-baby#bottom-story-socials

[127] Ng, Eric, "Caught Between Trump and its biggest market, America's sole rare earths mine is an unusual victim in the U.S.-China trade war," South China Morning Press, May 26, 2019. Available at: https://www.scmp.com/business/commodities/article/3011687/caught-between-trump-and-its-biggest-market-americas-sole-rare.

[128] HRPT-117-13, House Markup Energy and Water Bill (HRPT-117-13), "Thorium Molten-Salt Reactor Program," pp. 132-133, July 16, 2021.

[129] Senate Bill 2014 S. 2006, 113th Congress (2013-2014) "National Rare Earth Cooperative Act of 2014" [NRECA – H.R. 4883 & S. 2006]", introduced by Senator Blunt, February 6, 2014. Available at: https://www.congress.gov/bill/113th-congress/senate-bill/2006/text.

[130] Senate Bill 2019 S. 2093, 116th Congress, First Session, " RE-Coop 21st Century Manufacturing Act: A Bill to provide for the establishment of the Thorium-Bearing Rare Earth Refinery Cooperative, and for other purposes," introduced by Senator Rubio, July 11, 2019. Available at: https://www.congress.gov/bill/116th-congress/senate-bill/2093/text.

industrial non-nuclear applications. This bill or its updated version were passed, it would (a) develop domestic refining capacity to process domestic rare earth element deposits and waste sites; (b) benefit the U.S. economy by allowing for the rapid development and control of intellectual property relating to commercial development of thorium utilization technologies; (c) could lower REE production costs; and (d) ensure domestic sources of key REE materials, reducing dependence on Chinese REE supplies.[131]

By creating a thorium cooperative, the U.S. could simultaneously solve the REE and thorium radioactive contamination problem. U.S. and international REE end-users could directly invest in this cooperative supply-and-demand chain.[132] A thorium cooperative could produce what is needed (oxides, metals, alloys, standardized magnets, and components, etc.). The owner end-users could purchase their value-added rare earth goods at “market prices” (now set by China) and excess inventory could be sold to non-owners at ‘market prices’ with premiums for profits that could be redistributed back to the owners. All owner-members of the cooperative would ultimately acquire their value-added REE goods at cost, free of Chinese price manipulation or tariffs or any price control by other speculators.

Since thorium and REEs are typically waste byproducts from monazite mining for other commodities (e.g., phosphates, aluminum) the thorium and REE production and storage costs could be very low, or at least offset by REE extraction sales. Today the U.S. mining industry could meet 50 percent of global rare-earth demand from ongoing non-rare earth mining operations if the naturally-occurring radioactive thorium “contamination” were removed. The management and safe storage of unirradiated thorium does not pose any technical problems. Long-term thorium storage costs can be defrayed with a small surcharge paid by end-user members and non-members who purchase the finished rare earth products. Cooperative owners of the thorium storage facility would be given legal ownership and Congressional authority to develop industrial uses and markets for thorium, including nuclear energy.

U.S. thorium demand for nuclear fuel and non-nuclear applications could possibly be solved by removing thorium from existing monazite mining waste tails so that valuable REEs could be extracted and refined for the U.S. critical needs economy. The removed radioactive thorium could be safely stored in “bank” facilities for future nuclear fuel and non-nuclear applications. Phosphate minerals in monazites contain key REEs, thorium and uranium that can be extracted easily from the mining “tails”. The need for REEs, potential future use of thorium for nuclear fuel and non-nuclear thorium applications could make the extraction of thorium from monazite wastes an important national activity, especially for environmental cleanup.

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[131] IBID

[132] Kennedy, J. C., J. H. Kutsch, “Creating a Multi-National Development Platform: Thorium Energy & Rare Earth Value Chain,” International Atomic Energy Agency URAM - Symposium on Uranium and Raw Materials for the Nuclear Fuel Cycle: Exploration, Mining, Production, Supply and Demand, Economics & Environmental Issues, IAEA Headquarters, Vienna Austria, June 23 – 27, 2014.

X. Thorium Legislative History

This section of the report discusses past legislative action on thorium issues. It is provided for informational purposes only, and its inclusion in this report should not be construed as an endorsement by DOE.

Thorium extracted as a byproduct of the extraction of other minerals could be safely and separately stored for future use. A thorium "bank" could be used to store thorium obtained as a residual from rare-earth mining waste recovery in order to protect the environment from naturally radioactive thorium.[133,134,135] The thorium "bank" concept has been proposed in two Senate bills and supported by the Thorium Energy Alliance. Senator Rubio introduced his bill "RE-Coop 21st Century Manufacturing Act: A Bill to provide for the establishment of the Thorium-Bearing Rare Earth Refinery Cooperative, and for other purposes" in 2019.[136] Senator Blunt also submitted a similar bill with the same thorium bank concept in 2014.[137]

Section 5.b of the Rubio 2019 bill explicitly defines the Thorium Bank Concept as a "Thorium Storage, Energy, and Industrial Products Corporation," that would: (a) on a preprocessing basis, assume liability for and ownership of all thorium and mineralogically associated or related actinides and decay products contained within the rare earth element ores utilized by the Cooperative; (b) take physical possession and safely store all thorium-containing actinide byproducts, with the costs of the storage to be paid by the Cooperative; and (c) manage the sale of all valuable actinide and decay products, utilizing the proceeds for the development of commercial uses and market for thorium, including energy. Furthermore, the Corporation would establish at least one thorium storage facility, known as a "Thorium Bank" that would: (1) provide safe and long-term storage for all thorium produced as a byproduct in the production of rare earth elements for the Cooperative; and (2) hold and maintain financial surety bonding and insurance consistent with private industry standards.

Thorium for non-nuclear applications and future U.S. thorium-based reactor concepts would not have to be mined directly but could come from separating waste thorium nitrates, oxides,

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[133] Kutsch, John, "Concerned Experts in the Development of Thorium as an Alternate Nuclear Fuel and for Other Applications," Thorium Energy Alliance, presentation April 16, 2021.

[134] Kutsch, John, "Concerned Experts in the Development of Thorium as an Alternate Nuclear Fuel and for Other Applications," Thorium Energy Alliance, presentation April 16, 2021.

[135] Takashi, Kamei, "Implementation Strategy of Thorium Nuclear Power in the Context of Global Warming," in Nuclear Power--Deployment, Operation and Sustainability, edited by Pavel V. Tsvetkov, published September 9, 2011, DOI: 10.5772/704, ISBN: 978-953-307-474-0, eBook ISBN: 978-953-51-6045-8.

[136] Senate Bill 2019 S. 2093, 116th Congress, First Session, "RE-Coop 21st Century Manufacturing Act: A Bill to provide for the establishment of the Thorium-Bearing Rare Earth Refinery Cooperative, and for other purposes," introduced by Senator Rubio, July 11, 2019. Available at: https://www.congress.gov/bill/116th-congress/senate-bill/2093/text.

[137] Senate Bill 2014 S. 2006, 113th Congress (2013-2014) "National Rare Earth Cooperative Act of 2014" [NRECA – H.R. 4883 & S. 2006]", introduced by Senator Blunt, February 6, 2014. Available at: https://www.congress.gov/bill/113th-congress/senate-bill/2006/text

or metallic dust from the extraction of rare earth materials during the processing of monazite "tails" located at waste sites. The supply of thorium depends on supply and demand of rare-earth materials from mining waste recovery operations.

More recently the House of Representatives' Markup of the Energy and Water Bill contained specific language regarding DOE's thorium MSR programs[138] that stated:

"Thorium Molten-Salt Reactor Program.—The Committee is aware of both interest in and concerns with thorium molten-salt reactors (TMSR). The Department is directed to provide to the Committee not later than 90 days after enactment of this Act a report indicating whether the Department is working with any other nations to develop TMSR programs. The report should also include suggestions and considerations for Congress regarding the development of a domestic TMSR program, including the potential benefits and challenges of the technology, necessary infrastructure investments, fuel cycle considerations, proliferation issues, and the potential for using the federal U–233 supply and any resulting impacts to cleanup milestones or costs of cleanup or security activities related to the supply."

In May 2022, Senator Tuberville introduced the "Thorium Energy Security Act of 2022" in Senate Bill No. 4242. The bill provides for the preservation and storage of U-233 to foster development of thorium molten-salt reactors. It directs the Secretary of Energy to preserve U-233 inventories that have not been contaminated with U-238. It calls for reports on long-term and interim storage of U-233 and a report on the construction of a U-233 storage facility at Redstone Arsenal, Alabama. It also calls for reports on the use of thorium reactors by People's Republic of China, the medical market for isotopes of U-233, and the costs to the U.S. nuclear enterprise with respect to disposition of U-233, payments to nuclear facilities to store nuclear waste, and restarting the manufacturing in the U.S. of high-assay, low-enriched uranium.

XI. Summary

With the challenges discussed in this report for thorium-fueled reactors, NE continues to focus on uranium-based reactors and does not plan to initiate a separate ongoing thorium reactor development program. It should be noted that while DOE monitors thorium-fueled reactor research, development, and deployments internationally, NE is not currently working with any other nations to develop TMSR programs.

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[138] HRPT-117-13, House Markup Energy and Water Bill (HRPT-117-13), "Thorium Molten-Salt Reactor Program," pp. 132-133, July 16, 2021.

The U.S. does not have any existing thorium fuel cycle infrastructure. Scientists have suggested that it would take at least 5 years and $25 billion to design and deploy a viable thorium demonstration reactor.[139,140] Building a U.S. thorium fuel cycle infrastructure to support thorium fueled reactors would be very expensive and would take many years to license and deploy. The economic benefit for nuclear fuel vendors and utilities to potentially use thorium fuel in future yet-to-be-licensed reactor designs is a significant impediment when uranium fuel is relatively inexpensive, has been licensed for years, and more advanced accident tolerant uranium fuel designs are becoming available soon.

Thorium fuel utilization poses some significant challenges. Currently no thorium infrastructure exists in the U.S. Building a new thorium infrastructure that includes thorium fuel fabrication, fuel shipments, reactor licensing especially for mixed uranium and thorium and Th/U/Pu core designs, spent fuel recycling and processing in heavily shielded hot cells, spent fuel storage and shipping, etc., may cost much more than just continuing to use uranium-only fuel. If irradiated thorium fuel is reprocessed to recover fissile U-233 for subsequent Th/U-233 reactor fuel loadings, then THOREX processing could be used. DOE does not advocate any fuel reprocessing at this time. However, if fuel reprocessing were to be considered, the THOREX process used to remove thorium from spent fuel is more complicated than using either the UREX process used to recover U-235 or the PUREX process used to recover U-235 and Pu isotopes together for MOX fuel fabrication.

Irradiating thorium fuel produces fissile U-233 which presents a significant proliferation problem. Although thorium can be “denatured” by adding depleted or natural uranium, irradiation of thorium isotopes produces three protactinium isotopes Pa-231, Pa-232, and Pa-233, that eventually decay into pure U-233. Protactinium isotopes can be easily chemically separated from irradiated thorium fuel. Pa-233 with its 27 day half-life decays into pure U-233, so isolating Pa-233 produced during thorium irradiation may pose a serious proliferation issue. Significant gamma shielding and remote handling is required for any irradiated thorium fuel storage and reprocessing.

Thorium fuel may be useful for future Generation IV reactor designs, including advanced MSRs that would use natural and/or depleted uranium with its fissile U-235 content to “denature” fertile thorium fuel that would produce fissile U-233 as Th-232 is irradiated over the core lifetime. Mixed thorium and uranium fuel assemblies could be used in current LWRs or advanced LWRs in heterogeneous (i.e., seed-and-blanket LWR designs) core loading strategies that would be able to breed or burn fissile U-233. Thorium could be used in sodium fast reactor

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[139] Surampalli, Sameer, “Is Thorium the Fuel of the Future to Revitalize Nuclear?” Power Engineering, August 13, 2019, Available at: https://www.power-eng.com/nuclear/reactors/is-thorium-the-fuel-of-the-future-to-revitalize-nuclear.

[140] Idaho National Laboratory, “Advanced Fuel Cycle Cost Basis Report: Module A2 Thorium Mining and Milling,” DOE-NE Systems Analysis and Integration Campaign, Idaho Falls, 2021, INL/EXT-21-61493, Rev. 1.

blanket regions to produce fissile U-233 which could be used later in central core assembles to enhance overall minor actinide burning. Such thorium fuel cycle options may be able to increase fuel burnup, extend fuel resources, reduce the need for uranium enrichment facilities and uranium mining, and lower spent fuel volumes and waste radiotoxicity over time.

U.S. thorium demand for nuclear and non-nuclear applications may be aided by removing thorium during REEs extraction from monazite mining wastes. Thorium is nearly always bound to REE minerals in waste ponds and residual “tails” inventories as byproducts of phosphate, iron, coal, and titanium mining activities. Phosphate minerals in monazite “tailing ponds” have very high concentrations of key REEs, thorium and uranium, enough for U.S. and international REEs demand levels.[141,142]

Separating naturally radioactive thorium from monazite mining wastes would allow for the safe extraction of REEs from existing phosphate monazite mining waste streams. Thorium can be extracted from monazite “tails” thus eliminating the need for any direct deep-mining of thorium. The removed thorium may be able to be safely and separately stored in thorium “bank” facilities for fueling future nuclear reactors and non-nuclear applications. Several existing U.S. monazite waste sites could be remediated and supply current and future U.S. and world-wide REE demand if thorium was removed to facilitate the REE extraction process.[143,144]

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[141] Ault, Timothy, Bradley Van Gosen, et al., Natural Thorium Resources and Recovery: Options and Impacts. Nuclear Technology, Vol. 194, No. 2, May 2016, pp. 136-151.

[142] Ault, Timothy, Steven Krahn, Allen Croff, “Assessment of the Potential of By-Product Recovery of Thorium to Satisfy Demands of a Future Thorium Fuel Cycle,” Nuclear Technology, Vol, 189, No. 2, February 2015, pp. 52-162.

[143] Ault, Timothy, Bradley Van Gosen, et al., Natural Thorium Resources and Recovery: Options and Impacts. Nuclear Technology, Vol. 194, No. 2, May 2016, pp. 136-151.

[144] Ault, Timothy, Steven Krahn, Allen Croff, “Assessment of the Potential of By-Product Recovery of Thorium to Satisfy Demands of a Future Thorium Fuel Cycle,” Nuclear Technology, Vol, 189, No. 2, February 2015, pp. 52-162.

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Appendix A - Transmutation, Neutron Capture, and Decay Chains

Thorium is a radioactive chemical element with atomic number 90 and has an atomic weight 232.0377 in nature. All known thorium isotopes are unstable. The most stable isotope, Th-232, has a half-life of 14.05 billion years, and it decays very slowly via alpha (2n, 2p) decay first to Radium (Ra-228) in long decay chain that ends with the stable lead isotope Pb-208. On Earth, thorium and uranium are the only significantly radioactive elements that still occur naturally in large quantities as primordial elements. Thorium, discovered in 1828, was first used in 1885 when Carl von Welsbach invented the gas mantle as a portable source of incandescent light when heated by burning gases. Thorium's radioactivity was discovered in 1898 by Gerhard Carl Schmidt and later that year, independently, by Marie Curie. By 1950 thorium was replaced in many non-nuclear uses because of concerns about its radioactivity.

As a fertile[145] material, thorium fuel must be mixed with fissile uranium or plutonium to generate fission neutrons that Th-232 can capture which leads to the production of an alternative fissile isotope, U-233, and the coproduction of the highly radioactive isotope, U-232, which provides a high radiation barrier to discourage theft and proliferation of spent fuel as shown in these isotopic equations:

$$^{232}_{90}\mathrm{Th} + ^{1}_{0}n \rightarrow ^{233}_{90}\mathrm{Th} \rightarrow ^{233}_{91}\mathrm{Pa} + \beta \rightarrow ^{233}_{92}\mathrm{U} + \beta\ .$$

$$^{232}_{90}\mathrm{Th} + 3\mathrm{n} \rightarrow ^{233}_{90}\mathrm{Th} + \gamma + 2\mathrm{n} \xrightarrow[\text{21.8 min}]{\beta^-} ^{233}_{91}\mathrm{Pa} + \mathrm{n} \xrightarrow[\text{27.0 days}]{\beta^-} ^{233}_{92}\mathrm{U} \xrightarrow[1.60 \times 10^{5}\ \mathrm{y}]{\alpha}$$

Figure A-1 shows the reactor neutron irradiation transmutation process in the thorium fuel cycle in terms of neutron captures and radioactive decay. Figure A-2 compares the thorium Th-232 neutron capture/decay chain that produces U-233, with the U-235 neutron capture/radioactive decay chain that produces Pu-239 when they undergo neutron irradiation in a reactor.

Natural thorium produces radioactive "daughter" products as shown in Figure A-3 that emit both alpha and beta particles at various energy levels and half-life intervals so that unirradiated thorium is radioactive and needs to be handled carefully.

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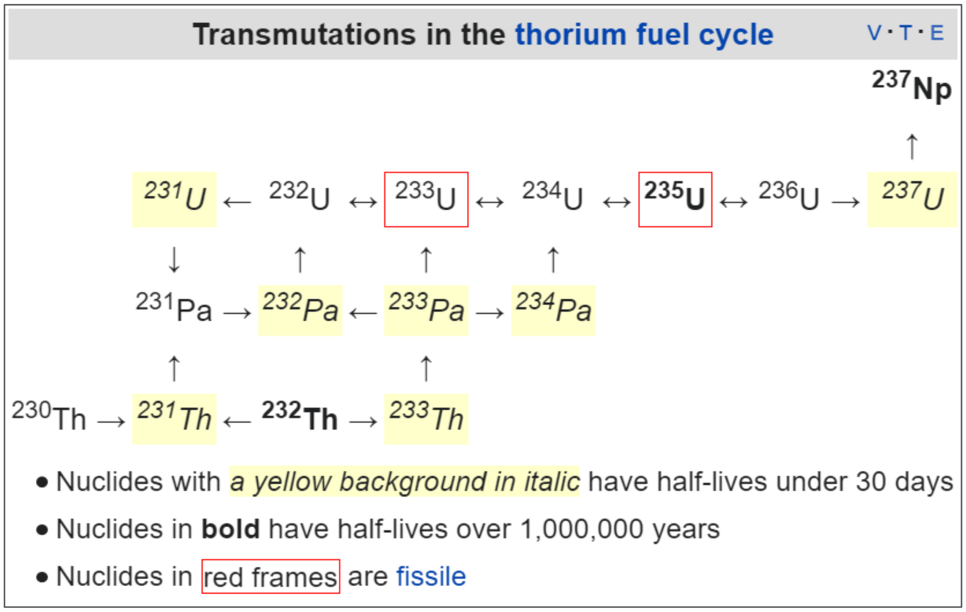
[145] "Fertile" fuel materials (special isotopes that will not support a nuclear chain reaction) may be changed into "fissile" fuel materials (isotopes that will support a nuclear chain reaction) by neutron irradiation in a nuclear reactor.

Figure A-1. Transmutations in the thorium fuel cycle



Transmutations in the thorium fuel cycle

- Nuclides with *a yellow background in italic* have half-lives under 30 days
- Nuclides in **bold** have half-lives over 1,000,000 years
- Nuclides in red frames are fissile

Figure A-2 Comparison of Fertile Th-232 and U-238 neutron capture and decay chains

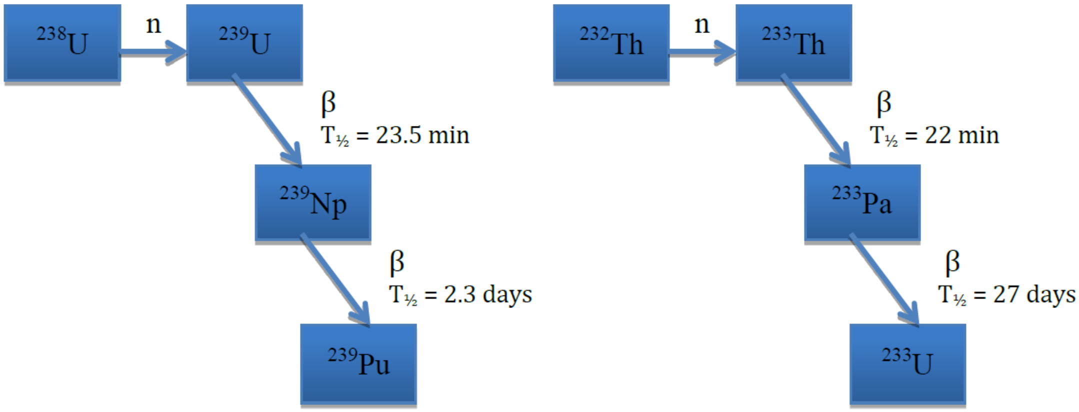
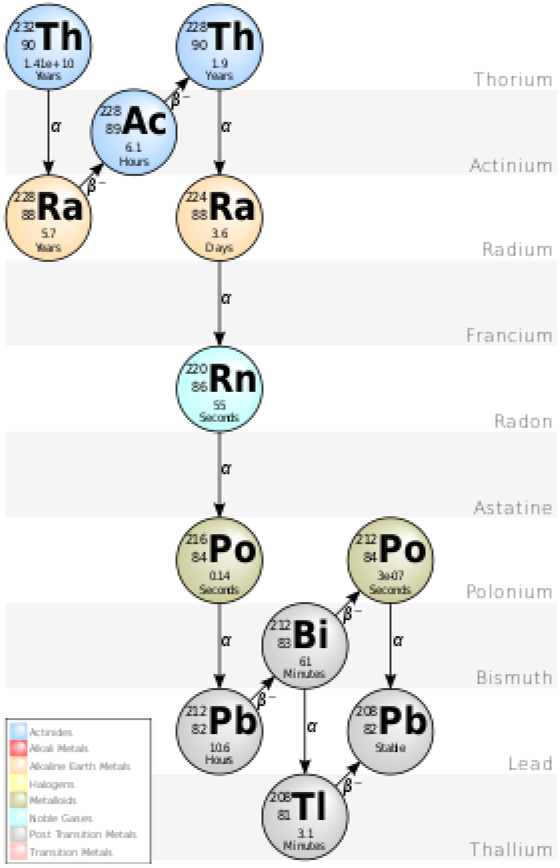


Figure 3.1. Capture and decay chains for ^{232}Th and ^{238}U.

Figure A-3 Th-232 decay chain to Pb-208



The 4*n* decay chain of ^{232}Th, commonly called the "thorium series"

Appendix B - Thorium Resources Inventory

Thorium is three to four times more abundant than uranium in the earth's crust. The average abundance of thorium in the earth's crust is 9.6 ppm compared to uranium at 2.7 ppm.[146] The concentration of these deposits needs to be considered when evaluating how economic it is to mine thorium. The recent NEA/IAEA Red Book Report's Table 2.1 states that there is a world total of 5.4 million metric tons of thorium for reasonably assured and inferred resources (i.e., recoverable at a cost of $80/kg), which is comparable with the amount of known economically recoverable uranium.[147] This estimate is based on approximating uranium and rare earth resources, because there is no international standard classification for thorium resources and thorium is not currently a primary exploration target. Thorium is usually extracted as a byproduct of mining other materials. Thorium is mostly found with the rare earth phosphate mineral, monazite, which contains up to about 12 percent thorium phosphate, but usually is only 6–7 percent on average. World monazite resources are estimated to be about 12 million tons, two-thirds of which are in heavy mineral sands deposits on the south and east coasts of India. There are substantial deposits in several other countries, as shown in Table B-1.[148]

The IAEA estimate of reasonably assured reserves (RAR) and estimated additional reserves (EAR) of thorium in 2005[149,150] and in 2007[151] is provided in Table B-2. Thorium is recovered mainly from the mineral monazite as a by-product of processing heavy-minerals and deposits for titanium-, zirconium-, or tin-bearing minerals. Information on thorium resources is produced jointly by the NEA/IAEA and published in Red Books biannually. The terminology used earlier as "Reasonably Assured Resources" and "Estimated Additional Resources I and II" are now identified as Inferred and Prognosticated Resources, respectively.

The USGS Office in the U.S. Department of the Interior has performed numerous studies to identify the indigenous thorium resources and has evaluated the details about the types of deposits, quality and geology of the thorium deposits and the rare earth materials surrounding

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[146] International Atomic Energy Agency, Thorium Fuel Cycle -- Potential Benefits and Challenges, IAEA- TECDOC 1450, Vienna, May 2005.

[147] Nuclear Energy Agency, "Uranium Resources, Production and Demand," The Redbook, A Joint Report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency, published biannually, NEA No. 7209, 2014; NEA No. 6345 2008, etc., Available at: https://www.oecd-ilibrary.org/nuclear-energy/uranium-2020_d82388ab-en.

[148] Nuclear Energy Agency, "Uranium 2007: Resources, Production and Demand," The Joint OECD Nuclear Energy Agency and the International Atomic Energy Agency, NEA No. 6345, Paris, France, 2008.

[149] International Atomic Energy Agency, Thorium Fuel Cycle -- Potential Benefits and Challenges, IAEA- TECDOC 1450, Vienna, May 2005.

[150] Nuclear Energy Agency, "Uranium Resources, Production and Demand," The Redbook, A Joint Report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency, published biannually, NEA No. 7209, 2014; NEA No. 6345 2008, etc., Available at: https://www.oecd-ilibrary.org/nuclear-energy/uranium-2020_d82388ab-en.

[151] Nuclear Energy Agency, "Uranium 2007: Resources, Production and Demand," The Joint OECD Nuclear Energy Agency and the International Atomic Energy Agency, NEA No. 6345, Paris, France, 2008.

these locations using previous studies and legacy information from the former U.S. Bureau of Mines.[152] Large volumes of known high-grade thorium resources exist in U.S. veins.[153,154] The USGS, as of 2010, estimated that the USA has reserves of at least 440,000 tons of thorium ore. The Lemhi Pass district of Montana-Idaho and the Wet Mountains area of Colorado (Fig. B-1), dominate the known high-grade thorium reserves in the U.S. (Table B-3). Some of these sites have already been developed for mining. The mining tails have radioactive thorium and rare earth materials that could be separated and harvested for use. Dense thorium-bearing minerals, chiefly the mineral monazite, occur in the black sand heavy-mineral concentrations of some stream and beach deposits. The alluvial deposits have been mined in the past by placer methods (sluicing, dredging). Notable examples shown in Figure B-1 occur in Idaho, North and South Carolina, and in northeastern Florida–southeastern Georgia. These alluvial deposits have low thorium concentrations and have practical advantages favoring their development to extract thorium and easier separation of heavy-mineral concentrates and rare earth minerals.[155]

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[152] Van Gosen, B.S., Gillerman, V.S., and Armbrustmacher, T.J., 2009, "Thorium deposits of the United States—Energy Resources for the Future?", U.S. Geological Survey Circular 1336. Available at: https://pubs.usgs.gov/circ/1336/pdf/C1336.pdf.

[153] U.S. Geological Survey, Thorium Statistics and Information: Mineral commodity summaries, published annually, U.S. Geological Survey, Reston, VA. Available at: https://www.usgs.gov/centers/nmic/thorium-statistics-and-information#mcs.

[154] Gambogi, Joseph, Department of the Interior, U.S. Geological Survey, 2016 Materials Yearbook, Thorium [Advance Release], May 2019. Available at: https://prd-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/atoms/files/myb1-2016-thorium.pdf

[155] Van Gosen, B.S., Gillerman, V.S., and Armbrustmacher, T.J., 2009, "Thorium deposits of the United States—Energy Resources for the Future?", U.S. Geological Survey Circular 1336. Available at: https://pubs.usgs.gov/circ/1336/pdf/C1336.pdf.

Table B-1 World thorium reserves (2007)[156]

Country	Tons	%
Australia	489,000	18.7%
U.S.	400,000	15.3%
Turkey	344,000	13.2%
India	319,000	12.2%
Brazil	302,000	11.6%
Venezuela	300,000	11.5%
Norway	132,000	5.1%
Egypt	100,000	3.8%
Russia	75,000	2.9%
Greenland (Denmark)	54,000	2.1%
Canada	44,000	1.7%
South Africa	18,000	0.7%
Other countries	33,000	1.2%
World Total	**2,610,000**	**100.0%**

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[156] Data taken from Uranium 2007: Resources, Production and Demand, Nuclear Energy Agency (2008), NEA No. 6345.

Table B-2 World thorium resources (1,000 tonnes Th)[157]

Country	**RAR** < USD 80/kgTh	**EAR I (Inferred)** <USD 80/kgTh	**Identified Resources** <USD 80/kgTh	**Prognosticated**
Australia*	46	406	452	NA
Brazil*	172	130	302	330
Canada	NA	44	44	128
Egypt	NA	100	100	280
Greenland	54	NA	54	32
India	319	NA	319	NA
Norway	NA	132	132	132
Russian Fed.	75	NA	75	NA
South Africa	18	NA	18	130
Turkey	344	NA	344	400 – 500
USA	122	278	400	274
Venezuela	NA	300	300	NA
Others	23	10	33	81
Total	**1,173**	**1,400**	**2,573**	**1,787 – 1,887**

NA Data not available. * Based on updated assessments.

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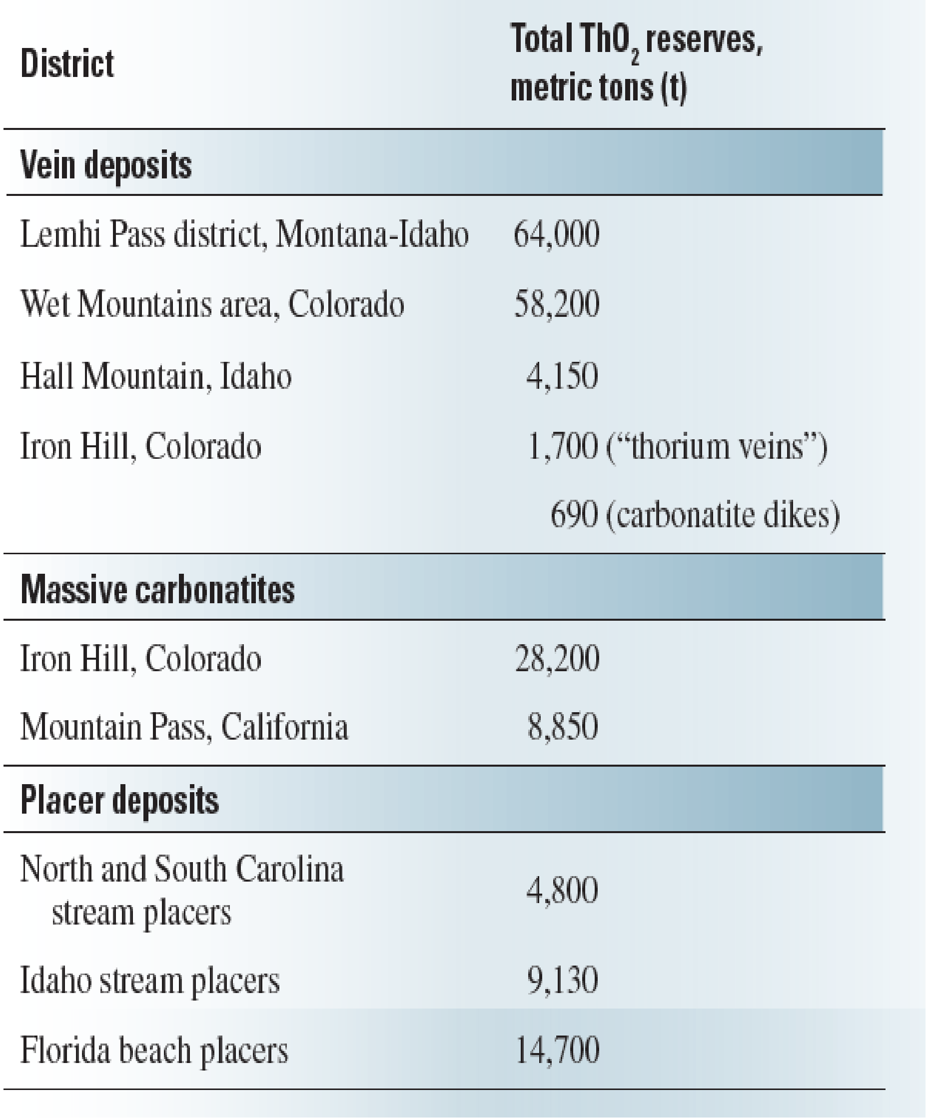
[157] Data taken from Uranium 2007: Resources, Production and Demand, Nuclear Energy Agency (2008), NEA No. 6345

Table B-3 Estimated Reserves of ThO_2 in the U.S.[158]



District	Total ThO_2 reserves, metric tons (t)
Vein deposits	
Lemhi Pass district, Montana-Idaho	64,000
Wet Mountains area, Colorado	58,200
Hall Mountain, Idaho	4,150
Iron Hill, Colorado	1,700 ("thorium veins") 690 (carbonatite dikes)
Massive carbonatites	
Iron Hill, Colorado	28,200
Mountain Pass, California	8,850
Placer deposits	
North and South Carolina stream placers	4,800
Idaho stream placers	9,130
Florida beach placers	14,700

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[158] Van Gosen, B.S., Gillerman, V.S., and Armbrustmacher, T.J., 2009, "Thorium deposits of the United States—Energy Resources for the Future?", U.S. Geological Survey Circular 1336. Available at: https://pubs.usgs.gov/circ/1336/pdf/C1336.pdf.

Figure B-1 Thorium Deposits in the United States[159]

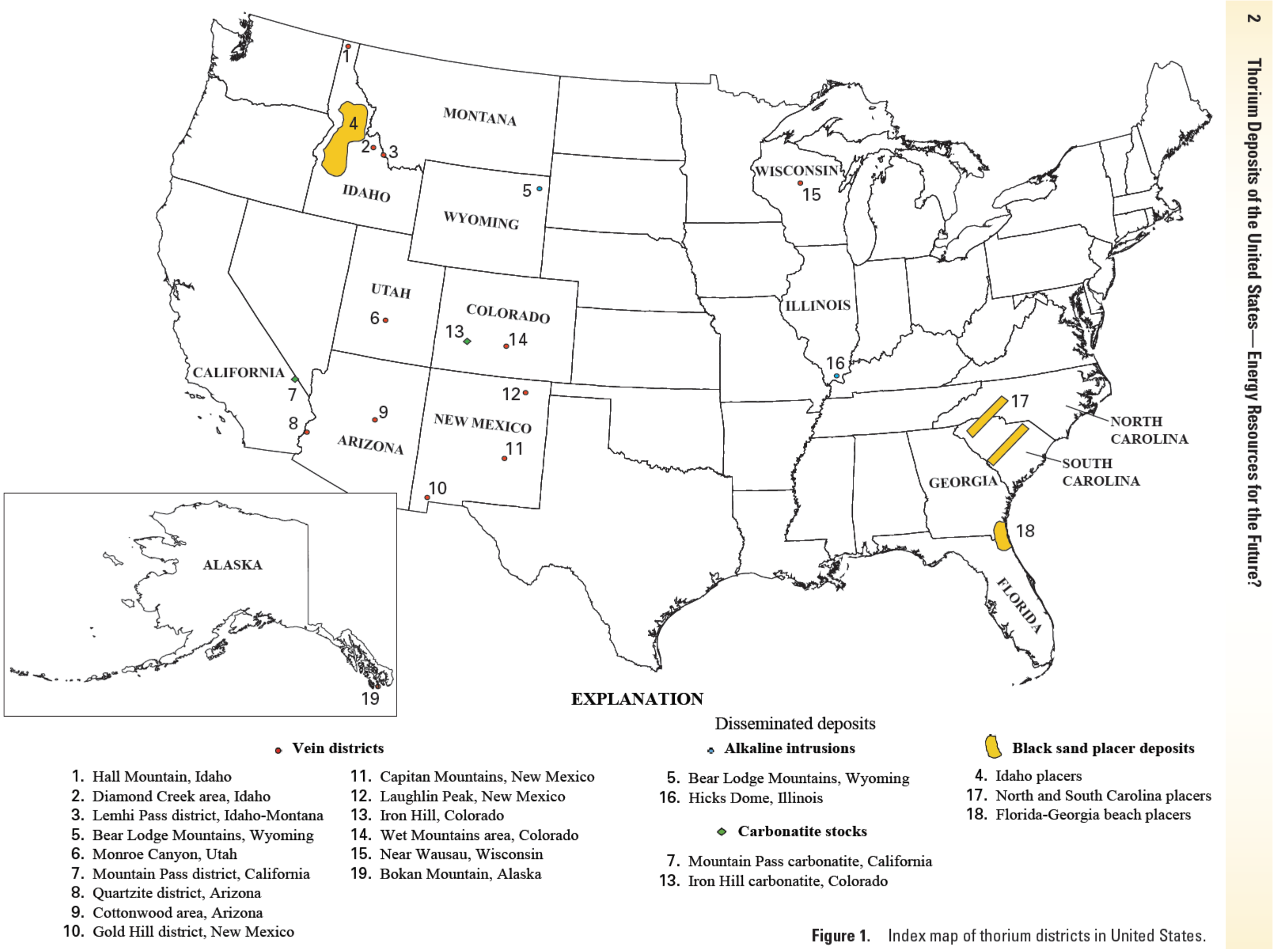

Figure 1. Index map of thorium districts in United States.

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[159] Van Gosen, B.S., Gillerman, V.S., and Armbrustmacher, T.J., 2009, "Thorium deposits of the United States—Energy Resources for the Future?", U.S. Geological Survey Circular 1336. Available at: https://pubs.usgs.gov/circ/1336/pdf/C1336.pdf.