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Research Article

Thorium – A Prospective Source of Energy

MNH Comsan*

Egyptian Atomic Energy Authority, Cairo, Egypt

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***Corresponding author:** MNH Comsan, Egyptian Atomic Energy Authority, Cairo, Egypt,
E-mail: comsanmn@hotmail.com

ORCiD: https://orcid.org/0000-0001-8706-2746

https://www.engineegroup.com

Abstract

The rising problem of fossil fuel reserve limitation along with environmental constraints connected with climate change and the necessity to reduce CO$_2$ emissions led to the recognition of nuclear energy as green energy. Currently, nuclear energy amounts to ~10% of the global generating electricity of ~4300 GW. Of the three known nuclear fuel elements: thorium, uranium, and plutonium, most of the operating nuclear reactors use uranium or a mix of uranium-plutonium as their fuel. As a result of using such a fuel for more than 50 years, a huge amount of long-lived hazardous radioactive waste has been accumulated. On the other hand, thorium as a nuclear material has several advantages over uranium. Among others, the advantages include favorable nuclear properties, along with much reduced nuclear waste. The article includes an overview of thorium as a prospective natural source of future energy. It deals with world thorium reserves (including in Egypt), the rationale of the thorium-based fuel cycle, the reasons behind the selection of thorium fuel, and issues to be considered while dealing with the thorium nuclear fuel cycle.

Introduction

The world is facing the reality of increasing energy demand and depleting natural energy resources. The increase is dictated by several reasons among them are population increase, economic **development** and increased urbanization. In 2022 primary energy production totaled 631.6 EJ, of which 88.76% are fissile fuel, 6.76% are renewables, and 4.48% are nuclear. Climatic change mitigation requires about 87% reduction of CO$_2$ emissions, the major source of which is the burning of fissile fuel, in the next 40-50 years, in order to keep the mean global temperature increase below 1.5 °C. Most energy analysts find that the replacement of conventional fissile fuel with near-zero carbon emissions sources cannot be done, in this period at least, by renewable sources alone [1-3].

On the other hand, nuclear fission energy (NE) has incomparable advantages over other conventional energy systems in solving the conflicts between the rapid growth of energy needs and environmental protection because of its high energy density, low carbon emissions, and the potential for sustainable development [4].

Interest in the uses of thorium as fuel for nuclear fission reactors has accompanied the dawn of various diversifications in the design and testing of these reactors since the mid-1950s, when the Oakridge National Laboratory in the United States of America designed and operated the “Molten Salt Reactor Experiment” (MSRE), in which it operated successfully at high temperatures and constant normal pressure. It operated at a capacity of 7.4 MWth, using different salts for both the coolant and fuel circuits. In the fuel department, uranium-235 was used during the period 1965-68, then uranium-233 during the period 1968-69 [5].

During the seventies, different designs for molten salt reactors were studied, using molten salts of a mixture of uranium and thorium or plutonium and thorium in the fuel circuit. Later, research and development programs demonstrated the simplicity of design, operation, and maintenance of this type of reactor and its suitability to operate at higher capacities for various purposes such as generating electricity or converting/burning nuclear waste [6].

As for electricity production, the IAEA 2023 estimates based on a constant 11% nuclear share, suggest a 19% increase in NE

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to 464 GWe in operation in 2030 (from the 2022 371 GWe) and to 674 GWe in 2050 [7,8].

The present work is to provide an overview of thorium use as a prospective natural source of future energy. It deals with world thorium reserves (including in Egypt), the rationale of the thorium-based fuel cycle, the reasons behind the selection of thorium fuel, and issues to be considered while dealing with the thorium nuclear fuel cycle.

Rational of nuclear energy

Nuclear energy systems offer many potential advantages yielding sustainable energy production [9]. These include:

Proven technology

Nuclear fission energy, in peaceful use since 1955, with decades of operating experience as a proven energy source (440 reactors with ~ 19000 reactor* years operating experience producing about 9% of world 2023 electricity) can make a serious contribution to carbon emission reduction in the next 30 years.

Extended life for fuel

Present nuclear reactors, mostly light water reactors require enriched uranium for their operation. Reprocessing of spent nuclear fuel to extract plutonium is seen as a requirement in the longer term due to the limitation of uranium resources. The use of thorium in the fuel mix adds to fuel life extension and reduces spent fuel burden.

Base load generation

Conventional nuclear power provides a constant energy output, so it is ideal to supply a base-load generation. NPPs can operate in a load-following mode with other base-load plants (fossil fuel, or hydro) to provide 24x7 constant power output.

Proliferation resistant

Both enrichment and reprocessing technologies have been for many years recognized as proliferation-sensitive. Most countries utilizing peaceful use of nuclear power follow the safeguards regime of the IAEA, which aims to prohibit non-peaceful use of nuclear technologies.

The problem of nuclear waste

Current generations of nuclear power reactors burn essentially low-enriched ^{235}U. They use less than 1% of the natural uranium, leaving the remaining (> 99%) as radioactive waste [10]. A typical 1 GWe LWR unit using ^{235}U fuel in a year generates ~ 37 tons of used nuclear fuel (NF) [11]. According to US EIA over the past four decades, US nuclear industry has produced ~ 76.4 kt of used NF, expected to reach ~ 162 kt by 2050. In 2016 the world nuclear industry generated a total of ~ 15.5 kt of used NF, expected to reach ~ 26.4 kt in 2050. This means that in 2050 a total accumulated inventory of ~ 732 kt of used NF will be added to the 327 kt accumulated till the year 2015.

Hence, for the lifetime of the nuclear industry fleet, total accumulated nuclear waste may account for ~1 Mt of spent nuclear fuel. Of which ~ 250 kt of highly radioactive spent fuel (responsible for more than 95% of the accumulated radioactivity) are distributed across some 14 countries.

Need for change: Thorium *vs.* Uranium

Thorium-232 is 3-4 times more abundant than uranium. Thorium is available in India, Brazil, Australia, the USA, Egypt Turkey, and many other countries. It is not a fissile material but it can produce U-233 in a nuclear reactor. From the neutronic standpoint, U-233 is an excellent nuclear fuel as compared to other fissile materials namely U-235, and Pu-239.

Thorium dioxide is the only stable oxide of thorium, which accounts for its greater stability compared to uranium dioxide. It is much more resistant to chemical interactions and has a high thermal conductivity.

Thorium produces much less minor actinides from fission, reducing dramatically the amount of spent fuel nuclear waste.

Thorium fuel fabrication is similar to U-fuel. However, it requires remote operation because of the gamma emission from the U-232 decay chain.

In addition, the high chemical inertness of thorium dioxide makes it very difficult to be dissolved and reprocessed. Because of these properties, the thorium fuel cycle is considered a more proliferation-resistant nuclear fuel [12,13].

Thorium resources

Table 1 gives in situ estimated 2020 continent distributed world thorium resources. The reserves are compared with the world 2022 in situ total uranium reserves of 7660 kt [14].

Thorium resources in Egypt

Egypt is considered one of the countries with high resources of thorium ore and ranks Fifth in the world with on-site resources of approximately 380 thousand tons of thorium

Table 1: Identified thorium resources.

Continent	Region	Total Resources kt Th (in situ)
Africa	North Sahara	410
	South Sahara	244
Americas	North	606
	South	1287
Asia	Central	1530
	East	115
	South-East	35
	South	867
	West	260
Australia		474
Europe	East	215
	West	520
World total (Th)		6563
World total (U)		7660

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(according to data from the European Nuclear Agency for the year 2016), which is, approximately 6.25% of the known and estimated global reserves. Egypt's estimate of these resources dates back to the 1960s and 1970s, and most of it is located within the black sand belt on the Mediterranean coast, extending from Alexandria in the west to Al-Arish in the east. Recently, there has been increasing interest in exploring thorium and uranium deposits in the mountains of the Eastern desert and in the Abu Zenima area in South Sinai. Table 2 shows in situ thorium resources, as well as Reasonably Assured Reserves (RAR) for the first seven countries having in situ resources [14].

Black sands in Egypt

Occurring along the Mediterranean coastal plain North of the Nile Delta, especially at the Nile outpourings near Rosetta and Damietta are beach placers deposited from the Nile stream during flood seasons reaching the Mediterranean Sea at river mouths.

Two types of black sands: the concentrated ore - very dark in color and contains 70- 90% of heavy minerals, and the diluted ore - lighter in color and contains up to 40% of HM.

BS contain some economic minerals such as ilmenite, hematite, rutile, magnetite, zircon, garnet, and monazite [14]. Some areas were studied in detail, and resources of economic minerals in the Rosetta area were estimated at 1000 tons [15,16].

Table 3 gives an analysis of a separated monazite sample. As is clear thorium content is ~ 10 times more than the uranium content [17].

Rationale of Th-based Fuel

The thorium element is of higher natural abundance (10 ppm) characterized by ease of mining operations. Oxide (ThO_2) melting point is ~3370 °C, the highest among all oxides. Thorium is very insoluble, which is why it is plentiful in sands but not in seawater, in contrast to uranium. ThO_2 has higher chemical and radiation stability. Excellent performance of thorium compounds: ThO_2, $(Th,U)O_2$, ThC_2, and $(Th,U)C_2$ as fuel in HTGRs.

^{232}Th–^{233}U fuel cycle is effective in burning long-lived transuranics in fast neutron reactors of a 'once–through' cycle, hence reducing the spent fuel nuclear repository burden. It has excellent possibility as fuel in CANDU–PHWR, ACR, and AHWR.

The thorium fuel cycle does not produce plutonium, the entry door to nuclear waste. The use of thorium–fuel in Accelerated Driven Systems (ADS) is more advantageous than uranium for nuclear fuel breeding [18,19].

Importance of nuclear fuel breeding

Nuclear fuel is not renewable by itself. Current nuclear power fleets using the once-through fuel cycle may exhaust all currently known uranium reserves within 100-200 years. The use of known thorium reserves may extend the fuel lifespan for an additional 300 years. Prolonging the lifespan of nuclear fuel could be achieved using two techniques:

1- Reprocessing of the accumulated spent fuel to recover the remaining valuable fissile isotopes (>98% of the originally used virgin fuel). The process could be repeated, however with little improvement of the remaining nuclear waste

2- Using breeder reactors that generate more fissile material than they consume. Breeder reactors could, in principle, extract almost all of the energy contained in uranium or thorium, decreasing fuel requirements by a factor of 100 compared to the widely used once-through nuclear reactors. Here thorium is the best choice for fuel breeding covering a wide range of neutron energies from thermal to fast [20,21].

While calculating the time required to provide the equivalent of total primary energy, the following data were used: world total U resources 7.66 Mt, world total Th resources 6.56 Mt, U from phosphate reserves 20 Mt, U from seawater 4000 Mt, total 2022 primary energy 631,6 EJ, modern 1GWe PWR reactor requires 29 tUO_2 out of 245 tU_3O_8, modern non-breeder reactor can pull 60 MWd/kg, while a breeder reactor – 900 MWd/kg [22-24].

The time durations given in Table 4 are compared with World global reserves that are estimated to last: Oil – 53 years, Gas – 85 years, and Coal – over 220 years.

Conclusion

The use of both uranium and thorium fissile materials is essential to meet current and future energy demands. Thorium has the potential to contribute towards a more sustainable nuclear electricity production, including more efficient resource utilization, much less spent fuel burden, and lower

Table 2: Thorium in situ and proven reserves for some countries.

Country	India	Brazil	USA	Australia	Egypt	Turkey	Venezuela
Thorium resources on site (kt)	846	632	595	595	380	374	300
Proven reserves (RAR) (kt) (130 USD/kg)	319	172	122	76	100	NA	NA

Table 3: Concentration in monazite mineral (85% purity), analysed by XRF.

Metal Oxide	$(REE)_2O_3$	ThO_2	U_3O_8
%	58.7	4.6	0.5

Table 4: Time providing 100% of primary energy (years).

	Non-breeders	Non-breeders	Breeders	Breeders	Breeders
Nuclear Fuel	Mined U	Mined U & Phosphate deposits	Mined U	Mined U&Th	Mined U&Th & 20% Sea-water U
Fuel Mass, Mt	7,66	~28	7.66	14.22	~ 814
Years	7.4	27.3	9,43e+2	1.75e+3	1.0e+5

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lifecycle emissions. Advancement in nuclear fuel technology is vital for better use of known conventional and nonconventional resources of fissile materials.

The development of fast breeder reactors and the use of closed and thorium-based fuel cycles may extend at large the lifetime of nuclear energy generation.

Considerable effort and investment are still needed to develop and characterize new fuel compounds for use in future generations of nuclear reactors operating at high temperatures and high power density.

More research and development are to be directed towards the use of homogenous reactors for isotope production and molten salt reactors for power generation.

References

1. Planete Energies. Global energy mix from 2022 to 2050. Available from: https://www.planete-energies.com/en/media/infographic/world-energy-mix-2022-2050
2. Statista. Primary energy consumption worldwide from 2000 to 2023. Available from: https://www.statista.com/statistics/265598/consumption-of-primary-energy-worldwide/
3. Nuclear Energy and Climate Change. Available from: https://www-pub.iaea.org/MTCD/publications/PDF/PAT-002_web.pdf
4. Benedict M, Pigford TH, Levi HW. Nuclear chemical engineering. 2nd ed. New York: McGraw-Hill Book Company; 1981.
5. Sorensen K. Lessons for the liquid-fluoride thorium reactor (from history). Mountain View, California, USA; 2009.
6. Chang H, Yang Y, Jing X, Xu Y. Thorium-based fuel cycles in the modular high temperature reactor. Tsinghua Sci Technol. 2006;11(6):731-738. Available from: https://doi.org/10.1016/S1007-0214(06)70257-7
7. International Atomic Energy Agency. Trend in electricity supplied 2004-2023. Available from: https://pris.iaea.org/PRIS/WorldStatistics/WorldTrendinElectricalProduction.aspx
8. Our World in Data. Energy mix. Available from: https://ourworldindata.org/energy-mix
9. World Nuclear Association. World nuclear performance report 2022. Available from: https://world-nuclear.org/our-association/publications/global-trends-reports/world-nuclear-performance-report-2022
10. Greenpeace. The global crisis of nuclear waste. GP France; 2018. Available from: https://www.greenpeace.org/static/planet4-belgium-stateless/2019/03/f7da075b-18.11.gp-report-global-crisis-of-nuclear-waste.pdf
11. U.S. Energy Information Administration. U.S. spent nuclear fuel inventory steadily increased from 2013 through 2017. May 2021. Available from: https://www.eia.gov/todayinenergy/detail.php?id=47796
12. Jyothi RK, Tumajan LG, De Melo C, Santos RM, Yoon HS. An overview of thorium as a prospective natural resource for future energy. Front Energy Res. 2023;11. Available from: https://doi.org/10.3389/fenrg.2023.1132611
13. Lung M. A present review of the thorium nuclear fuel cycles. EUR 17771 EN; 1997. Available from: https://op.europa.eu/en/publication-detail/-/publication/c8aaf356-d913-460e-b145-08c258c4ef76/language-en
14. World thorium occurrences, deposits and resources. IAEA-TECDOC-1877; 2019. Available from: https://www.iaea.org/publications/13550/world-thorium-occurrences-deposits-and-resources
15. El Shazly EM. Thorium resources in the United Arab Republic and their possible utilization. IAEA TE 52; 1966. Available from: https://inis.iaea.org/collection/NCLCollectionStore/_Public/24/075/24075231.pdf
16. Shain MA, Saad EA, Shazly A, Ezzat A, El-Mongy SA. Evaluation of rare earth elements in black sand and phosphate ores—Egypt. Egypt J Chem. 2020;63(11):4185-4193. Available from: https://doi.org/10.21608/ejchem.2020.21042.2305
17. Abd El Fattah AIL. Commercial approach for highly pure thorium from Egyptian monazite mineral acid process. IOP Conf Ser: Mater Sci Eng. 2020;975:012022. Available from: https://iopscience.iop.org/article/10.1088/1757-899X/975/1/012022
18. Thorium fuel cycle: potential benefits and challenges. IAEA-TECDOC-1450; 2005. Available from: https://www.iaea.org/publications/7192/thorium-fuel-cycle-potential-benefits-and-challenges
19. Todosow M. Thorium-based fuels for PWRs. In: Thorium Energy Conference; 2011; New York City.
20. Cochran TB, Feiveson HA, Patterson W, Pshakin G, Ramana MV, Schneider M, et al. Fast breeder reactor programs: history and status. International Panel on Fissile Materials; 2010. Available from: https://fissilematerials.org/library/rr08.pdf
21. Rubbia C. The energy amplifier. In: Proc. 8th Journées de SATURNE; 1995; Saclay, France.
22. Tulsidas H, Hilton J, Haldar TK. Uranium extraction from phosphates. In: URAM; 2014 Jun 23–27; IAEA. Available from: https://www-pub.iaea.org/iaeameetings/cn216pn/Thursday/Session13/213-Haldar.pdf
23. Lightfoot HD, Manheimer W, Meneley DA, Pendergast D, Stanford GS. Nuclear fission fuel is inexhaustible. 2006 IEEE EIC Climate Change Conference; 2006. Available from: http://dx.doi.org/10.1109/EICCCC.2006.277268
24. Touran N. Nuclear fuel will last us for 4 billion years. Available from: https://whatisnuclear.com/nuclear-sustainability.html

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