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Thorium for Sustainable Nuclear Energy

Rafika HELAIMIA

Department of English, Universityof MCM, Soukahras,Algeria

r.helaimia@univ-soukahras.dz

Abstract – Since the 1950s, there has been interest in using thorium in the nuclear fuel cycle as a primary source of nuclear energy. This is due to its practicality and its likelihood of not becoming scarce in the future. However, in the 2000s, there was a revolution in the international arena to address environmental, economic, and political issues such as global warming, greenhouse gas emissions, depletion of fossil fuels, nuclear proliferation dangers, lack of energy access, and insecurity. The goal of implementing a new nuclear strategy is to substitute thorium for uranium as a source of nuclear energy. This is because thorium is naturally abundant and helps to reduce the risk of nuclear accidents and radioactive contamination. Nevertheless, certain nations have faced obstacles in altering their nuclear approach, mainly due to concerns about the risks associated with nuclear proliferation. But, there are ongoing endeavors to realize a significant climate change stabilizing wedge through the implementation of thorium-based reactors. This article explains the properties of thorium, outlines the advantages of using it, and highlights any limitations to its application, with the aim of addressing these concerns.

Keywords – Thorium, Sources, *Uranium, Drivers, Energy, Limitations*

I. Introduction

There has been a lot of interest in using thorium as a part of the nuclear fuel cycle since the 20th century. This interest has increased due to issues such as the need to reduce greenhouse gas emissions and find a new, reliable, and cost-effective energy source. To achieve more sustainable and diverse sources of energy, strategies and scenarios have been proposed. One such strategy is thorium nuclear energy production, which some countries have adopted despite challenges and restrictions. This is because they believe that more nuclear energy is necessary for economic and secure development. Thorium has favorable characteristics such as abundance, lack of long-lived α emitters, and reduced greenhouse gas emissions.

II. Overview of Nuclear Fuel Sources and Production

As we strive for global progress, it is crucial to ensure a reliable energy supply and promote sustainable energy sources. Despite a decline in some developed countries, the demand for electricity is expected to increase in the future due to population growth. Meeting this growing demand is essential for achieving energy security and sustainable development goals (1). Nuclear power is widely considered the most cost-effective and eco-friendly energy source due to its low cost and minimal gas emissions. Many countries are expected to increase their nuclear power capacity to 82% by 2025 from 7% in 2015 (2). Uranium and thorium are commonly used to produce nuclear energy.

- *Uranium*

Uranium is a commonly found element in the earth's crust and is primarily used as fuel in reactors. In its natural state, uranium is composed of 99.3% 238U, 0.7% 235U, and small amounts of 234U. To be utilized in the nuclear fuel cycle, it must first be separated from its ore and converted into a usable form.

Uranium extraction involves various techniques, including open-cut and underground mining. Sometimes, copper mining can lead to the discovery of uranium as a byproduct. The usual method of processing mined uranium ores is to grind them into a uniform consistency and then extract uranium with chemical leaching. This process often results in the creation of "yellowcake," a dry powder that contains about 75% naturally occurring uranium. The "yellowcake" is then sold as U_3O_8 on the uranium market(3).

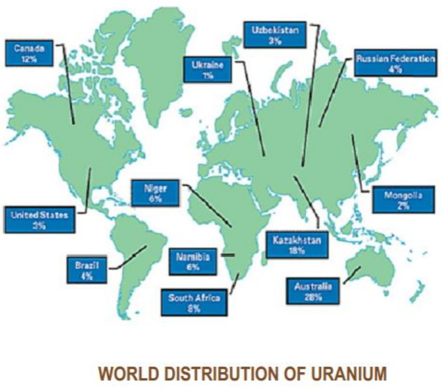

Fig.1 Uranium global distribution (https://www.selfstudyforias.com/uranium-and-thorium/)

- *Thorium*

Thorium is being considered for use in the fuel cycle due to its ability to reduce minor actinide production, as per the IAEA in 2012. Over the past fifteen years, research on thorium-based fuels for current or evolutionary (generation III+) reactors has gained more attention. Thorium can be a useful addition to the uranium-plutonium fuel cycle, as it can help manage radioactive waste and spent fuels, and provide a solution for dealing with plutonium stockpiles without fast reactors. Additionally, thorium may offer flexibility in light of uncertainties about the long-term availability of reasonably priced uranium (15).

The primary source of thorium is the mineral phosphate monazite, which has the highest concentration of thorium among other minerals with a ThO_2 content ranging from 3.1% to 11.34% (16).

To extract thorium from the mineral monazite two main processes are required: acid digestion and leaching. During the acid digestion process, sulfuric acid is utilized to break down the monazite and is then heated to 230 C for four hours. Afterwards, a selective precipitation method is employed to separate thorium from uranium and rare earth elements (REE) using ammonium hydroxide (NH_4OH), sodium hydroxide (NaOH), and hydrogen peroxide (H_2O_2) (17) (18). It is confirmed that 97.68% of the thorium can be separated at a pH of 1.05e1.84 (19).

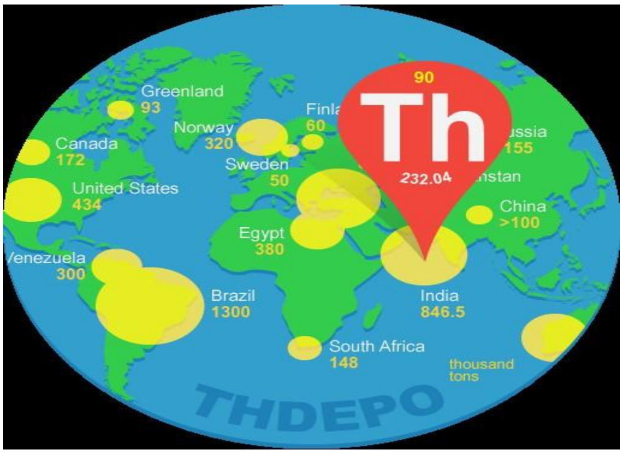

Fig.2 Thorium global distribution (https://www.pmfias.com/uranium-thorium-distribution-advantages-uranium-india-nuclear-power-plants)

III. Drivers of Thorium Consumption

Despite economic, environmental, and energy factors like the financial crisis, the Fukushima Daiichi accident in 2011, and the booming gas tendency affecting the development of nuclear energy production, a number of countries decided to develop the use of thorium to build new nuclear plans. Reasons include:

- *Thorium is abundant in nature.*

Thorium (Th) is an element that is three times more common in nature than uranium. The isotope 232Th accounts for the majority of natural thorium, while other isotopes may exist in trace amounts or be produced artificially. Thorium makes up only 0.0006% (6,000 ppb) of the Earth's crust, compared to uranium which makes up 0.00018% of the crust. Thorium is radioactive and has a half-life of 1.4 1010 years, while uranium-238 has a half-life of 4.5 109 years. Due to its longer half-life, thorium is more prevalent than uranium in the Earth's crust, with an average concentration of 7.2 ppm (parts per million). These characteristics demonstrate the unique nature of thorium.

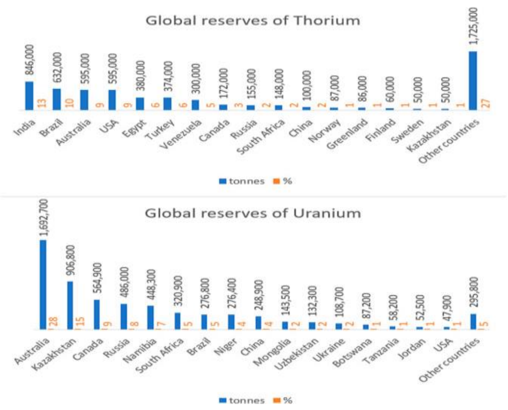

Fig.3 Thorium world reserves (https://www.frontiersin.org/articles/10.3389/fenrg.2023.1132611/full

- *Thorium is a Fertile Material*

Unlike uranium, which is fissile, thorium is a nuclear fertile source. Thorium (232Th) is a radioactive element that can capture neutrons and become 233Th, which then undergoes double beta decay to produce fissile 233U, a nuclear fuel (5). Besides, some of the Th232 transforms into U233 by absorbing neutrons inside a reactor, which is why thorium is classified as "fertile" instead of "fissile" .Uranium-232 is preferred over uranium-238 for producing waste that does not contain long-lived emitters because it hardly produces plutonium or other transuranic elements (6). Furthermore, adding thorium to ADS allows transuranium or plutonium to burn without requiring uranium-238. These systems not only have low radiotoxicity of waste but also provide improved safety features and greater breeding flexibility (7). Thorium is crucial for the sustainability of advanced nuclear reactor designs, like Generation IV and beyond, because its conversion ratio is equal to or greater than 1(8).

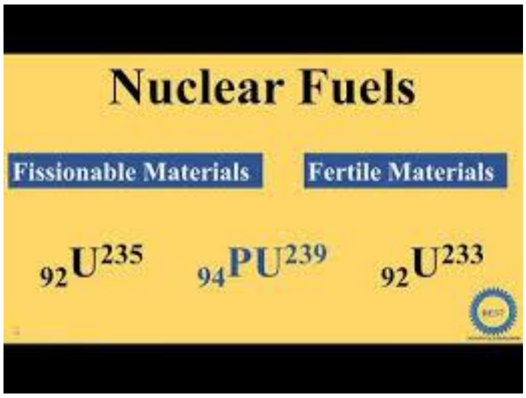

Fig. 4 Thorium materials

(https://academic-accelerator.com/encyclopedia/fertile-material)

- *Thorium is Potentially a Non-proliferation Breeder*

A potential solution for non-proliferation is the use of thorium as a matrix fuel. This can aid in burning additional fissile materials in an open fuel cycle mode. By combining thorium with other fuels, it is possible to create powerful fuels with highly enriched uranium or plutonium. These fuels can be used in reactors to improve the rate at which fissile material is consumed. As a result, this procedure can speed up the removal of potentially dangerous fissile material (14).

IV.THORIUM FOR NUCLEAR ENERGY PRODUCTION

The utilization of thorium as a new alternative source of energy has been a tantalizing prospect years ago. Thorium has been used as a source of energy since the end of World War II. Between 1950 and 1960, many advancements were made, including the development of multiple thorium prototypes. Currently, three main programs are focused on developing thorium nuclear fuel (7):

The long-term goal of the Indian program is to use Advanced Heavy Water Reactors for burning thorium, uranium-233, and plutonium.

The Molten Salt Reactor is one of six ideas created by the Generation IV International Forum (GIF).

Within the European Atomic Energy Community (Euratom) Research Framework Program, the Accelerator Driven System (ADS) idea is being developed. This system combines an accelerator, a spallation source, and a sub-critical reactor.

Thorium (Th-232) cannot be directly used in a thermal neutron reactor as it is not fissile on its own. However, it is considered "fertile" and can transform into uranium-233 (U-233) once it absorbs a neutron. U-233 is an exceptional source of fissile material, similar to how uranium-238 transforms into plutonium-239. Therefore, the initial radiation of Th-232 in a reactor is necessary to provide the required neutron dosing for the production of protactinium-233 in all thorium fuel concepts. The generated Pa-233 can be separated chemically from the parent thorium fuel, and the decay product U-233 can be recycled into new fuel. Alternatively, 'the U-233 can be used "in-situ" in the same fuel form, particularly in molten salt reactors (MSRs)' (12).

According to the International Atomic Energy Agency, Th232 has a higher absorption cross-section for thermal neutrons (7.4 barns) compared to U238 (2.7 barns) (9). This leads to a greater conversion to U233 when using Th232, as opposed to U238 (which converts to Pu239). Hania notes that U233 has a fission-to-capture ratio of about 10, whereas Pu239's ratio is only about 2.5. This information can be used to calculate the high neutron yield per absorption ratio (10). Besides, If a reactor generates more fissile material than it uses, it is called a breeder. This implies that, despite expected neutron losses, the excess neutrons can produce more nuclear fuel than is fissioned. Nuclear fission thorium breeder cycle reactors have the potential to increase the amount of fissile material by over 100 times(11). Moreover, Thorium is selected to be used in seven power reactions, The first five of these have all at some point been put into use. The final two are still ideas (12):

- *Heavy Water Reactors (PHWRs) :*

These reactors are well-suited for thorium fuels because of their (i) efficient neutron economy (less absorption of neutrons means more can be used by thorium to create U-233), (ii) slightly faster average neutron energy that promotes U-233 conversion, and (iii) ability to refuel online. Additionally, heavy water reactors, such as the CANDU, have extensive licensing experience and are a widely-used commercial technology .

- *High-Temperature Gas-Cooled Reactors (HTRs) :*

This type of fuel is well-suited for thorium-based applications. It consists of durable particles coated with "TRISO" and enriched uranium or plutonium mixed with thorium. The particles are then layered with pyrolytic carbon and silicon carbide, which effectively retain fission gases. The fuel is contained in a graphite matrix that remains stable at high temperatures. These fuels have the capacity to withstand prolonged exposure to radiation, allowing for thorough fissile burning. Both "pebble bed" and "prismatic" HTR reactors can utilize thorium-based fuels.

- *Boiling (Light) Water Reactors (BWRs) :*

In terms of rods with varying compositions (fissile content) and structural features allowing the fuel to experience more or less moderation (e.g., half-length fuel rods), BWR fuel assemblies can be designed with flexibility. This design flexibility is excellent for producing well-optimized thorium fuels and suitable heterogeneous arrangements. Therefore, it is possible to design thorium-plutonium BWR fuels that are specifically suited for "burning" extra plutonium. And perhaps most significantly, BWRs are a type of licensed reactor that is well -known.

- *Pressurised (Light) Water Reactors (PWRs):*

Viable thorium fuels can be designed for a PWR, though with less flexibility than for BWRs. Fuel needs to be in heterogeneous arrangements in order to achieve satisfactory fuel burn-up. It is not possible to design viable thorium-based PWR fuels that convert significant amounts of U-233. Even though PWRs are not the perfect reactor in which to use thorium, they are the industry workhorse and there is a lot of PWR licensing experience. They are a viable early-entry thorium platform.

- *Fast Neutron Reactors (FNRs) :*

In reactors with a fast neutron spectrum, a broader range of heavy nuclides can be fissionable and potentially used to fuel thorium. However, because U-238 has a higher fast-fission rate and residual U-235 contributes to fission in this material, using thorium as a fertile fuel matrix in these reactor systems is not particularly advantageous compared to depleted uranium (DU). Moreover, there is little competitive advantage to using thorium in these systems because there is a vast excess of DU that can be easily utilized when more FNRs are commercially available.

- *Molten Salt Reactors (MSRs):*

Even though they are still in the design phase, these reactors could be ideal for using thorium as fuel. The fuel would consist of a salt mixture that includes thorium and uranium (U-233 and/or U-235) fluorides, which would act as both a heat transfer fluid and a matrix for the fissioning fuel. The fluid would be processed to remove any harmful fission products or valuable U-233, and then circulated through the central region of the reactor. The amount of graphite used in the core would determine the level of moderation. Specific designs for thorium fuels would be needed to produce sufficient amounts of U-233.

- *Accelerator Driven Reactors (ADS):*

There is a new energy concept called the sub-critical ADS system which uses nuclear fission. This system may have the potential to use thorium as a fuel source. The process involves high-energy protons from an accelerator colliding with a heavy target such as lead to create spallation neutrons. These neutrons are then directed towards thorium fuel, like Th-plutonium, which produces heat as in a typical reactor. However, the system is subcritical and unable to support a chain reaction without the proton beam. High-energy accelerators have issues with reliability and cost due to their high power consumption.

It is worth noting that molten salt reactors are the best reactors for using thorium as nuclear fuel.

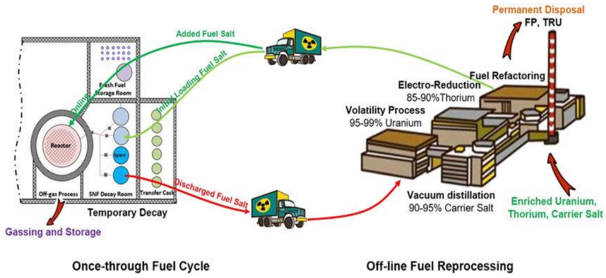

Fig. 5 Second stage Thorium molten- salt- reactor process

(Zhu-Guifeng/publication/The-fuel-cycle-mode-of-thorium-based-molten-salt-reactor-TMSR-at-the-second-stage.jpg)

V.LİMİTATİONS

Although thorium has potential benefits as a new type of nuclear fuel, certain countries face challenges and limitations in fully utilizing it. However, international programs are actively working to overcome these obstacles and make thorium a more feasible option for sustainable nuclear fuel. The United States Department of Energy's Nuclear Fuel Cycle Evaluation and Screening report from 2014 identified three main barriers that hinder the use of thorium in this capacity (14) :

1.The supporters of the thorium cycle had to give up the original cycle that relied on highly enriched uranium (HEU) due to its difficulty in production and potential use in nuclear weapons. Instead, they replaced it with low-enriched uranium (LEU) that is enriched to a maximum of 20%. This change made it more complicated to implement the thorium cycle and reduced its overall effectiveness ;

2.The United States banned the reprocessing of spent fuel, preventing the recovery of 233U from thorium-spent fuel for recycling ;

3.The use of partial recycling in the uranium/plutonium fuel cycle was fully developed and implemented in some countries, such as France, with no apparent restrictions.

VI.CONCLUSİON

The utilization of thorium in the nuclear fuel cycle has been the focus of interest for several countries, especially those having significant thorium reserves like Brazil. This is due to concerns about population growth, limited access to energy sources, depletion of fossil fuels, global warming, and the need for sustainable energy alternatives. Thorium has several benefits that could positively impact the nuclear fuel cycle. However, there are certain challenges associated with the use of thorium, particularly in regard to its radiotoxicity, which may impede its resurgence in popularity. To address this, it is recommended to conduct inter alia scientific research and implement programs to take advantage of the abundant supply of thorium found in nature. Emulating successful practices, such as India's use of thorium in nuclear reactors, can also be beneficial. may limit its potential.

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