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

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ABSTRACT

This paper presented a review on the past, present and the future of thorium fuel cycle. The aim of this study is to evaluate the developments in thorium fuel cycle, looking at the prospects and drawbacks on the possibility of thorium-based nuclear fuel for commercial reactors realising the increasing challenges of uranium-based nuclear fuel. The initial interest on thorium-based nuclear fuel and why it was abandoned at the early stage of nuclear technology were considered. Also, the reasons behind the present renewed interest on the viability of thorium fuel cycle as a valuable alternative to the conventional uranium-based fuel were studied. Thorium abundance, its physical, chemical and neutronic properties were evaluated in comparison to the uranium fuel cycle to determine thorium fuel sustainability for next generation nuclear industry. In this study, it was found that thorium fuel is three to four times more abundant, has higher conductivity, high melting temperature, low expansivity and more proliferation resistant compared to uranium fuel. The possible application and related challenges of thorium fuels in different reactor types and designs such as light water reactors (LWRs), high temperature gas-cooled reactors (HTGRs), heavy water reactors (HWRs), molten salt reactors (MSRs) and accelerator driven system reactors (ADSRs) were reviewed. The findings indicate that thorium fuel cycle can be used in the currently dominant LWRs designs in the nuclear industry with little technical modification, and also in other reactor types under investigation for future application especially molten salt breeder reactors, fast reactors and accelerator driven system reactors. Finally, this review made some recommendations on the short-term and long–term applications of thorium-based nuclear fuel cycle, and the issues that must be addressed before using thorium fuel for commercial reactor operations.

1. Introduction

It is a well-known fact that nuclear energy is at the centre of the world's debate politically, socially, economically and otherwise. This debate mainly is because of the increasing energy needs of the ever-growing world population, and how to manage all issues arising from the nuclear technology energy sources [1,2]. The prediction by the United States Department of Energy (US-DoE) that electricity demand will increase by 2035 is a pointer that a more reliable energy technology must evolve for commercial purposes. Since then, through relentless efforts, today many countries are meeting 20–40% of their energy needs from nuclear power using fissile uranium-235 and plutonium-239 based fuel cycles [3]. The interest in uranium-235 was due to its fissile nature compared to the Thorium-232 which is a fertile nuclear material [4,5].

However, the continuous depletion of uranium reserves, the vast production of both weapon and reactor grade plutonium and transuranic isotopes, issues of lack of waste repositories, and nuclear terrorism have raised serious global concerns on the continuous use of conventional nuclear reactors operating on uranium-based fuel [6,7]. Also, the withdrawal of the Yucca Mountain Repository licensing application by the US-DoE created more concerns on nuclear waste management [7,8]. Moreover, the unfortunate nuclear accidents (Three Mile Island and Chernobyl) of 1980s [9], and the US policy shift on energy investment, generally affected the advancement in nuclear industry. Despite the challenges associated with uranium-based fuel, many countries still have vested interest in well-established uranium-based fuel reactor, as other alternative such as use of thorium based nuclear fuel technology is still not available in application level. But issues arising from the continuous use of uranium-based nuclear fuel for

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the operation of over 80% reactors in existence, have greatly renewed an interest on thorium as an efficient option [10]. The most recent Fukushima Daiichi nuclear accident in Japan has equally negatively changed peoples' perception on uranium-based fuel reactors [11–14], thereby prompting greater demand for safer alternative energy sources. These issues have reawakened the need for a viable and safer nuclear fuel alternative that would reduce to a bearable minimum the challenges posed by the uranium-based nuclear fuel [15,16].

Thorium-based nuclear fuel has been of interest alongside uranium from 1950 to 1970. In fact, there are experimental and research reactors that operated on thorium-based nuclear fuel in the 1960s [17]. The 21st century has seen an increase in thorium related researches, but many has been on academic related publications and reports [17,18]. Currently, there is a renewed interest in the possible use of thorium-based fuel to generate nuclear power (electricity) at a commercial scale. India has maintained its quest for a commercial thorium-based fuel nuclear power due to their large thorium reserves with little or no uranium reserves. In fact, China and USA are currently collaborating in an intensive research programme on thorium utilisation in molten salt reactor designs [19]. Indeed, Generation IV reactor project funding which has a time frame of the year 2030, has thorium-based nuclear fuel fully recommended and incorporated molten salt cores and very high temperature gas cooled thorium-based TRISO-fuel reactors [8,20]. The renewed interest could also be attributed to the new Atomic Act on Peaceful Utilisation of Nuclear Energy and Ionising Radiation, which was published as Act No. 263/2016 Coll., replacing the previous Act No. 18/1997 Coll. This Act became effective from January 2017, and it is in fulfilment of IAEA and Euratom directives on nuclear energy utilisation [21].

This review is to evaluate the developments in thorium fuel cycle, looking at the prospects and drawbacks on the possibility of thorium-based nuclear fuel for commercial reactors keeping in mind the increasing challenges of uranium-based nuclear fuel. It also evaluated the type of reactor designs and configurations that would be suitable for this application.

2. Nuclear fuel resources

To meet the ever-increasing world population energy demand in a more environmentally friendly approach, attention has been shifted to the potential of nuclear energy that may play a greater role in the future energy mix. The sustainability of this energy mix is dependent on the availability of the sources of the nuclear energy fuel [22]. Generally, the survey and exploration of nuclear fuel resources to determine their world reserves are categorised into; conventional, unconventional and secondary resources. This categorisation is based on the naturally known and predictable resources of such potential fuel. The availability of thorium resources in large quantities is one of the strong factors encouraging and driving investors both government and private companies to committing their resources into the research [22].

Today, there is unarguably a reliable information on uranium nuclear fuel resources at various grades and levels based on the material and technological advancements made in its application in nuclear power both in military and civilian reactors. About 80% of reactors in operation worldwide are uranium-based PWRs and have been in operation for around a century. Many of the known reserves must have been depleted after a very long period of its application in reactor operation. The uranium reserves as shown in Table 1 is a clear reflection of small quantity of uranium available for current reactor operations. This shows the estimates of different categories of uranium resources by the year 2000. From the table, the undiscovered resources are over 75% of the total conventional resources while known conventional resources is less than 15%. This implies that the known will finish in no distance time. According to Red Book data 2010, the conventional uranium resources will last for more 75 years counting from 2001 at demand rate of 2,000tU per year [10,22,23]. The story is quite different for thorium, as information is sparsely available, due to lack of dedicated and continuous interest after series of events that made uranium a popular option at the period 1940s–1980s [24].

Table 1
World uranium resources categories [10].

Resource type	Estimate (1000 tU)
Known conventional resources	
Reasonably assured resources (RAR)	2850
Estimated additional resources I (EAR-I)	1080
Undiscovered conventional resources	
Estimated additional resources II (EAR-II)	2330
Speculative resources (SR)	9940
Secondary resources	
Commercial inventories	220
Surplus military inventories	250
Re-enrichment	440
Sub-total	**17,110**
Undiscovered resources	
In phosphates	22,000
In seawater	4,000,000
Grand total	**4,039,110**

2.1. Thorium availability

It has been widely reported that thorium is three to four times more abundant [4,25], in nature than the conventional uranium, based on its average concentration in the earth's crust. Thorium exists majorly as monazite ore in the earth's crust mixed with other rare earth elements (REEs). Monazite sand is found in large quantities in India, China, Brazil, United States of America, and as well as Australia. Today, thorium is entirely produced as a by-product in the extraction of rare earth elements or from the production of titanium or zirconium bearing minerals from monazite sand. This is because of low industrial demand of thorium, since it is yet to be used for commercial production of energy in nuclear reactors. Therefore, little exploration of thorium has been made, which clarifies why there is uncertainty on its total world reserves [18,26].

Table 2 provides information on the known thorium reserves for almost all the potential countries. Low technological advancement, little or no demand for the nuclide in large quantities, and its non-application in commercial reactors, made any investment on its survey and exploration unattractive many years ago. As interest in thorium-based fuel reactor has been renewed, there is hope that more thorium deposit sites shall be discovered and quantified, raising the resource reserves. Interestingly, the reported large availability and relative ease of extraction of thorium is a good incentive for its future large-scale production as a nuclear fuel [27].

3. Thorium as a nuclear fuel

The first study on the viability of thorium as a nuclear fuel started in USA almost the same time that of uranium and plutonium under Manhattan project [5]. Thorium (^{232}Th) as a fertile isotope undergoes nuclear transmutation to produce a fissile ^{233}U nucleus. By thermal neutron capture, thorium fuelled reactor produces ^{233}U by the following likely reactions in Eqs. (1) and (2). The fissile ^{233}U either fission during nuclear reaction or may be removed chemically from spent fuel, and then forms a new nuclear fuel. It is on record that 90% of bred ^{233}U fissions while only 10% goes into spent fuel, which represents a higher fuel burn-up compared to uranium [5,6].

However, to start up a thorium fuel cycle by fissioning ^{233}U, it entails providing enough fissile material in the reactor core. This could be done by the high enrichment of thorium with ^{235}U or ^{239}Pu. The enrichment of thorium for more than 19.9%, and high plutonium are not desirable from the proliferation and waste point of view, since this