OVERVIEW ON THORIUM IN RESEARCH REACTORS

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ABSTRACT

Thorium is a fertile material that can undergo transmutation for it to become a fissile material, uranium-233. The fissile material can go through a fission process in order to generate heat energy and eventually electricity. Most nuclear reactors use uranium as their fission source. The use of thorium as nuclear fuel has been only investigated for few types of reactors such as a high temperature gas reactor (HTGR), fast breeder reactor, light water reactor (LWR) and heavy water reactor (HWR). For research reactors specifically, there are limited academic publications related to the latest use of thorium. Hence, the main interest of this work is to compile and review the latest academic publications related to the active use of thorium for research reactors in particular. The reviewed studies have been divided into two categories which are experimental and simulation projects. The experimental projects are about the ongoing thorium fuel tests that have been carried out in an actual research reactor. On the hand, the simulation work is related to the computational analysis performed in predicting the neutronic behaviour of thorium based fuel in research reactors. The experimental study of thorium is currently active for the KAMINI research reactor. Additionally, most simulation works focus on finding criticality and neutron spectra.

ABSTRAK

Torium ialah satu bahan subur yang boleh menjalani pengubahan untuk ia menjadi satu bahan boleh belah, uranium 233. Bahan boleh belah boleh mengulang satu proses pembelahan dengan tujuan menghasilkan tenaga haba dan akhirnya bekalan elektrik. Kebanyakan reaktor nuklear guna uranium sebagai sumber pembelahan mereka. Penggunaan torium sebagai bahan api nuklear telah hanya disiasat kerana beberapa jenis reaktor (HTGR) seperti reaktor gas suhu tinggi, reaktor pembiak cepat, reaktor air ringan (LWR) dan reaktor air berat (HWR). Untuk reaktor penyelidikan secara spesifik , terdapat penerbitan ilmiah terhad berkaitan dengan penggunaan terbaru torium. Maka, bunga besar kerja ini adalah untuk mengumpulkan dan mengkaji semula penerbitan ilmiah terbaru berkaitan dengan penggunaan aktif torium untuk reaktor penyelidikan khususnya. Kajian-kajian mengkaji semula telah dibahagikan kepada dua kategori yang mana percubaan dan projek-projek simulasi. Projek percubaan tentang ujian-ujian bahan api torium berterusan yang telah dijalankan dalam reaktor kajian sebenar. Di tangan, kerja simulasi berkaitan dengan analisis berkomputer mempersembahkan dalam meramal kelakuan neutronic torium berpangkalan bahan api dalam reaktor penyelidikan. Kajian bereksperimen torium kini giat untuk reaktor penyelidikan KAMINI. Tambahan pula, kebanyakan simulasi bekerja fokus pada mencari spektrum kegentingan dan neutron.

Keywords: research reactor, thorium, KAMINI

INTRODUCTION

One solution to sustain nuclear energy is by introducing thorium as a fuel in nuclear reactors. One of the most popular technologies for thorium fuel is the usage of thorium in a molten salt reactor. The reactor uses aqueous thorium as the fuel in the reactor. Thorium (specifically thorium-232), however, is a fertile material, which means the element cannot undergo fission with thermal neutrons. It can still be transmuted to a fissile element, such as uranium-233 for nuclear fission to take place using thermal neutrons in a reactor core [1]. When thorium-232 is bombarded with neutrons, thorium-232 will absorb them and become thorium-233. Next, thorium-233 will undergo beta decay process and become protactinium-233. Later, protactinium will also decay (beta decay) to eventually become uranium-233. Figure 1 shows the transmutation process from thorium-232 to uranium-233.

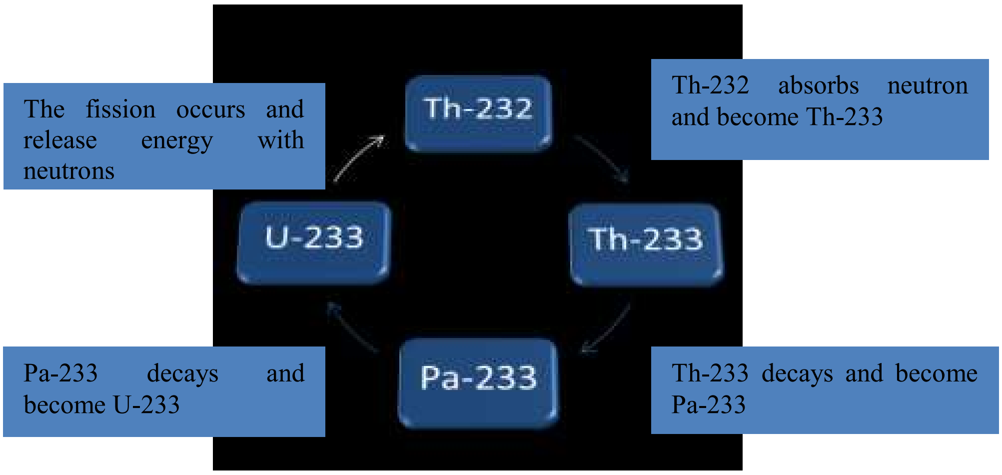

Figure 1: Transmutation process of thorium-232

THORIUM NUCLEAR REACTORS

Table 1: Reactors that have utilized thorium as fuel. Reproduced from Ref. [1].

No	Name and Country	Type	Power	Fuel	Operation Period
1	National Research Universal (NRU) & National Research Experimental (NRX), Canada	MTR (Pin Assemblies)	-	Th+^{235}U Test Fuel	1947-1992 1957-2009 Irradiation–testing of few fuel elements
2	Canadian-Indian Reactor Uranium System (CIRUS), India	MTR Thermal (PHWR)	40 MWt	Fuel ‘J’ rod of Th & ThO_2 (mainly natural uranium)	1960-2010
3	Borax IV & Elk River Reactors, United States of America (USA)	BWRs (Pin Assemblies)	2.4 MW(e) 24 MWt	Th+^{235}U Driver Fuel, Oxide Pellets	1963 - 1968

4	Indian Point 1, USA	PWR	275 MW	Th+^{235}U Driver Fuel	1962-1974 Thorium core was discontinued before well before 1974 because of poor performance
5	Molten Salt Reactor Experiment (MSRE) Oak Ridge National Laboratory (ORNL), USA	MSBR	7.5 MWt	^{233}U Molten Fluorides	1964 - 1969
6	Dragon, United Kingdom (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
7	Peach Bottom, USA	HTGR Experimental (Prismatic Block)	40 MW(e)	Th+^{235}U Driver Fuel, Coated fuel particles Oxide & Dicarbides	1966 – 1972
8	Arbeitsgemeinschaft Versuchs Reaktor (AVR), Germany	HTGR Experimental (Pebble bed reactor)	15 MW(e)	Th+^{235}U Driver Fuel, Coated fuel particles Oxide & dicarbides	1967 – 1988
9	Lingen, Germany	BWR Irradiation-testing	60 MW(e)	Test Fuel $(Th,Pu)O_2$ pellets	1968-1973
10	KEMA Suspension Test Reactor (KSTR) Keuring van Elektrotechnische Materialen te Arnhem (KEMA), Netherlands	Aqueous Homogenous Suspension (Pin Assemblies)	1 MWt	Th+ HEU Oxide Pellets	1974 - 1977
11	Fort St. Vrain, USA	HTGR Power (Prismatic Block)	330 MW(e)	Th+^{235}U Driver Fuel	1976 - 1989
12	Shippingport (3rd Core) , USA	LWBR PWR (Pin Assemblies)	60MW(e)	Th+^{233}U Driver Fuel, Oxide Pellets	1977 – 1982 1962- 1980
13	Thorium High-Temperature Reactor (THTR), Germany	HTGR Power (Pebble Type)	300MW(e)	Th+^{235}U, Driver Fuel, Coated fuel particles Oxide & dicarbides	1985 - 1989

14	Fast Breeder-Test Reactor FBTR, India	LMFBR (Pin Assemblies)	40 MWt	ThO_2 blanket	1985-Now
15	Dhruva Research Reactor, India	MTR Thermal	100 MWt	'J' rod of ThO_2	1985-Now
16	Kalpakkam Mini Reactor (KAMINI), India	MTR Thermal	30 kWt	Al-^{233}U Driver	1996-Now
17	Kakrapar Atomic Power Station (KAPS 1&2),Kaiga Generation Station (KGS 1&2), Rajasthan Atomic Power Station (RAPS 2,3&4), India	PHWR (Pin Assemblies)	220MW(e)	ThO_2 Pellets For neutron flux flattening of initial core after start-up	1995-Now 2000-Now 1981-Now

From Table 1, it can be seen that thorium has been primarily investigated by countries like Germany, the United Kingdom, the United States, Netherlands, Canada and mostly in India. Most thorium reactors (either research or power reactors) have a very short lifetime of operation. There are only four reactors remaining in operation with two of them are material testing reactors (MTRs), which are situated in Canada and India. The other two reactors are the liquid metal fast breeder reactor (LMFBR) and pressurized heavy water reactor (PHWR) that are situated in India. India has a vast amount of thorium resources compared to uranium resources [2] and hence there is a strong interest in thorium in the country compared to other nations. The research reactor in India, namely the Kalpakkam Mini Reactor (KAMINI), uses a by-product of thorium for its fuel. It is the only reactor that uses uranium-233 fuels for its core. The fuel is bred and supplied by India's Fast Breeder-Test Reactor (FBTR) that is situated next to the KAMINI reactor.

USAGE OF THORIUM IN RESEARCH REACTORS

Table 2 shows the publications related to the active use of thorium in research reactors. Currently, most thorium-based fuel studies are conducted in the KAMINI research reactor. Research activities carried out at the KAMINI reactor are associated with shielding, neutron activation analysis and neutron radiography [3]. Studies on the India research reactor and short findings are presented in rows 2, 3 and 4 of Table 2. Another work conducted in Mainz TRIGA research reactor in Germany is also listed in row 1 of Table 2. The study uses environmental sample from Egypt to determine uranium or thorium isotopes using neutron activation analysis. The samples were irradiated with thermal neutron flux $7x10^{11}$ n/cm^2 before being analyzed.

Table 2: Experimental findings from research reactors with thorium

No	Author	Year	Research Paper	Purpose	Findings
1	A. El-Taher	2004	Determination of traces of uranium and thorium concentration in some Egyptian environmental matrices by instrumental neutron activation analysis [4]	Determining thorium/uranium isotopes from environmental samples using neutron activation analysis from Mainz TRIGA	Uranium concentrations vary between 1.0 and 1.6 ppm, while thorium concentrations vary between 6.2 and 8.2 ppm

				reactor	
2	S. Usha	2004	Research reactor KAMINI [5]	Description of design, available facilities for experiment in KAMINI reactor	Services that can be provided by KAMINI reactor are neutron radiography for fuel, NR for pyro devices and NAA
3	P.N.Manoharan	2012	Fifteen Years of Operating Experience of KAMINI Reactor [3]	The specification of KAMINI Reactor that uses uranium-233 as fuel	KAMINI is the only reactor that use U-233 as fuel in the world
4	Sujoy Sen	2015	Determination of neutron energy spectrum at KAMINI shielding experiment location [6]	Comparing neutron spectrum with theoretical and experimental results	The neutron spectrum has been determined which and produce correctly compare with calculated spectrum.

Table 3 shows simulation works on thorium in research reactors and their findings. The simulation works related to the KAMINI research reactor are presented in rows 1 and 2 of Table 3. These studies measured neutron spectrum using a SAND-II code and calculated the core criticality using different cross section libraries and a Monte Carlo code. For row 3 of Table 3, study by Feghhi is about neutronic simulations on a research reactor core using the Monte Carlo code. The study used 19 uranium-thorium oxide $(U,Th)O_2$ fuel assemblies in hexagon structure with different arrangements of gap between fuel assemblies [7]. As for row 4 of the table, the work listed is about the study of thorium oxide fuel utilization in the existing core of TRIGA PUSPATI (RTP) reactor in Malaysia. The core of RTP has a circular array structure with six fuel rings. In the study, thorium was added in various rings of the RTP core [8]. The criticality was then calculated using an MCNP code and compared to that of the original reactor core without thorium.

Table 3: Simulation thorium in research reactor

No	Author	Year	Research Paper	Purpose	Findings
1	D.K. Mohapatra	2001	Measurement and prediction of neutron spectra in the Kalpakkam mini reactor (KAMINI) [9]	Measurement of neutron spectrum by multi-foil irradiation method at beam tube end using a SAND-II code	Using multi-foil irradiation method, neutron spectrum have been measured
2	C. Sunil Sunny	2007	KAMINI reactor benchmark analysis [10]	Criticality calculation with different cross sections libraries with U-233 as fuel	K_{eff} improved from 0.9890 to 0.99357
3	Seyed Amir Hossein Feghhi	2013	Neutronic simulation of a general research reactor core of $(^{232}Th, ^{235}U)O_2$	Neutron spectrum, actinides accumulation and criticality	Interspace between each fuel assembly has

			fuel using MCNPX2.6 code [7]	calculations by comparing different design of assemblies	given the max K_{eff} of 1.00026
4	Abdul Aziz Mohamed	2016	Simulation on TRIGA PUSPATI reactor core kinetics fueled with thorium (Th) based fuel element [8]	Criticality calculation of TRIGA reactor core with the addition of thorium fuel	K_{eff} = 1.13454 (thorium in ring b) K_{eff} = 0.90509 (thorium in ring c) K_{eff} = 1.16371 (thorium in ring d)

CONCLUSION

The experimental and simulation works of thorium in research reactors in particular are still in need of attention. Currently, most experimental studies are actively carried out in India and Canada. Simulation work related to thorium research reactors is primarily focused on calculations of criticality and neutron spectra. There are still other investigations that can be done for understanding the thorium based fuel behavior in a research reactor such as performing power peaking, burnup calculations and fuel cycle analysis.

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