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Advantages of Liquid Fluoride Thorium Reactor in Comparison with Light Water Reactor

Che Nor Aniza Che Zainul Bahri[1, a)], Amran Ab. Majid[1], Wadeeah M. Al- Areqi[1]

[1]*Nuclear Science Program, School of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia*

[a)]Corresponding author: anizazainul@gmail.com

Abstract. Liquid Fluoride Thorium Reactor (LFTR) is an innovative design for the thermal breeder reactor that has important potential benefits over the traditional reactor design. LFTR is fluoride based liquid fuel, that use the thorium dissolved in salt mixture of lithium fluoride and beryllium fluoride. Therefore, LFTR technology is fundamentally different from the solid fuel technology currently in use. Although the traditional nuclear reactor technology has been proven, it has perceptual problems with safety and nuclear waste products. The aim of this paper is to discuss the potential advantages of LFTR in three aspects such as safety, fuel efficiency and nuclear waste as an alternative energy generator in the future. Comparisons between LFTR and Light Water Reactor (LWR), on general principles of fuel cycle, resource availability, radiotoxicity and nuclear weapon proliferation shall be elaborated.

Keywords: Liquid Fluoride Thorium Reactor, Light Water Reactor, safety, nuclear waste, nuclear fuel

INTRODUCTION

Liquid Fluoride Thorium Reactor (LFTR) is one of modernized reactor design derived from Molten Salt Reactor (MSRs) concept. It is part of the Generation- IV reactor series by the Generation IV International Forum, which consists of the United State, United Kingdom, Canada, France, Japan, China, Russia and European Atomic Energy Community [J. Thorton, 2011]. LFTR is fluoride based liquid fuel that used the thorium dissolved in salt mixture of lithium fluoride (LiF) and beryllium fluoride (BeF_2) called as FLiBe. LFTR reactor design consists of a core and a blanket. Both hold the different mixture of molten salt. The blanket carries the irradiated liquid Thorium-232 (^{232}Th) into a decay tank where the Uranium-233 (^{233}U) can be removed to the inner core. The ^{233}U molten salt in the inner core will transfer heat to the heat exchanger which then drives a turbine to generate electricity [Lucas, 2013]. Historically, research on thorium based nuclear reactors began after World War II at Oak Ridge National Laboratory (ORNL), but in 1973, the USA government ordered all US researches on thorium to be terminated because uranium was considered more efficient and its by-product can be used to make nuclear weapon [Moir & Edward, 2005]. This results in most of the traditional reactors currently using the uranium in solid form as nuclear fuel.

Almost 85% of the total numbers of nuclear units in operation worldwide are Light Water Reactors (LWRs). LWRs can be subdivided into three categories: the Pressurized Water Reactor (PWR), the Boiling Water Reactor (BWR) and the Supercritical Water Reactor (SCWR). The uranium in these cores undergoes fission, which generates free neutrons to keep the nuclear chain-reaction going, as well as large amounts of heat for electricity generation. The water surrounding the reactor core acts as a coolant to ensure that the core does not get too hot and "melts down", as well as transporting the heat generated in the core to the steam generator for electricity generation [European Nuclear Society, 2013].

The LFTR technology is fundamentally different from LWR technology currently in use. The presence of long lived, high level radiotoxic elements in the waste from LWR is becoming a more significant issue, especially from a safety point of view [N. Cerullo, 2012]. In comparison LFTR has numerous operational and safety advantages, with

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many advanced countries see the great potential in this technology and are currently undertaking researches LFTRs or are searching for funding to do so, including Japan, Canada, China and the United States [N. Cooper et. al, 2011]. Thus, the aim of this paper is to discuss the potential advantages of LFTR with respects to its safety, fuel efficiency and nuclear waste, and as an alternative energy in the future. The comparison of LFTR and LWR on general principles of fuel cycle, resource availability, radiotoxicity and nuclear weapon proliferation will be discussed.

ADVANTAGES OF LFTR

LFTR have technological advantages in three particular areas: safety, fuel efficiency and lack of nuclear waste. Each of these will be briefly discussed to create a basis of understanding on how LFTR differs from conventional uranium-based reactor.

Inherent Safety Features

The reactor plant always been designed to have inherent safety features as it is the most important criteria. One of the main safety features in LFTR is that the reactors have atmospheric pressure during operation. An inherent danger of current nuclear power plant is the use of high pressure water to cool the reactor and remove the heat. In the current nuclear reactor, water serves as coolant and neutron moderator. The heat from fission causes water to boil, either directly in the core or in a steam generator that drives a turbine. The water is maintained at high pressure to raise its boiling temperature [Hargraves & Moir, 2010]. For LFTR, the cores are designed to operate at low pressure as the coolant liquid fluoride salts remain as liquid at high temperatures. The fluoride salts has high boiling temperature around 1400°C. Because of this, the fluoride salt does not need to be pressurized to remain as liquid and thus the reactor can be operated at atmospheric pressure. Without highly pressurized liquid, the LFTR does not risk explosions and would not require large containment infrastructure [Hargraves & Moir, 2010]. This safety feature using fluoride salt was approved long time ago. From 1960 to 1964, the Molten Salt Reactor Experiment (MSRE) was designed and built as a test fluoride power reactor. The MSRE was successfully operated for 4 years without accident. Between 1965 and 1968, MSRE was used to investigate the performance and technology needed to build a molten salt reactor, and it was safely operated above 700°C [Lam, 2013].

The second safety feature of LFTR is its negative temperature coefficient of reactivity. The negative temperature coefficient means that the regulation of the reactor's temperature is passive. There is no need for control rods or an active cooling system. As the core temperature increase, the salt expands. The expansions spread the fuel volumetrically and slow the fission rate. In the other words, as the reactor temperature rises, the reactivity decreases [Neil Endicott, 2013]. The reactor thus automatically reduces its reactivity if it overheats. It is because fluoride salt has an attractive thermal expansion characteristic that yields a strongly negative temperature coefficient of reactivity. The temperature dependence comes from three sources [Mathieu et. al, 2010]. The first is the Doppler Effect that thorium to absorb more neutrons when it overheats [Mathieu et. al, 2010]. This leave fewer neutrons to continue the chain reaction, and thus reducing the reactor power. The second effect is it has to do with thermal expansion of the fuel [Mathieu et. al, 2010]. If the fuel overheats, it expends considerably, due to the liquid nature of fuel which will push fuel out of the active core region. In a small and well moderated core, this reduces the reactivity. The third feature is the graphite moderator in the reactor that usually causes a positive contribution to the temperature coefficient [Mathieu et. al, 2010].

The other safety feature of LFTR is frozen salt plug. The fuel in LFTR is already in liquid form so it cannot melt down and in emergency situation it can be quickly drained out of the reactor into a passively cooled dump tank. A freeze plug made of frozen salt that is cooled by a fan to keep it at a lower temperature then the salt's melting point. If the core's temperature rises beyond a critical point, the frozen salt plug melts and the liquid fuel in the core is immediate evacuated by pouring it into a subcritical geometry in catch basin. In this basin, the reaction quickly stops because thorium is no longer being bred into ^{233}U by fuel the reaction. This is possible because the fuel is a molten salt liquid. The freezer plug safety feature was used in Alvin Weinberg's on 1965 in MSRE [Hargraves & Moir, 2010].

LFTR Fuel Efficiency

Fuel efficiency is a form of thermal efficiency. The efficiency of a process involves converting a chemical potential energy contained in a carrier fuel into kinetic energy or work. Efficiency goes up when heat flows through

a greater temperature difference, with the limit above absolute zero in degrees Kelvin (°K). The higher temperature of molten salt as compared to pressurized water contributes to LFTR high electric/ thermal efficiency. LFTR safely operates at high temperatures with the salt remains in liquid form below 1400°C. LFTR molten salt operates at temperature 700°C, compared to LWR at 315°C, enabling new, more efficient electric/thermal power conversion technology [Hargraves, 2012].

Traditional uranium fuelled reactors are not very efficient when converting uranium into energy. This is because only 3% of uranium put into the reactor is consumed before the fuel rod is switched out. One reason for this is the heat and radiation released in the reactor core damaged the solid uranium fuel rods, causes them to be taken out after a few years. The LFTR is much more efficient at converting thorium into energy than LWR because all of the fuel is burned up, with the thermal to electrical energy conversion rate of 45 – 50% instead of 30 – 35% [Hargraves & Moir, 2010; Hart, 2013]. It also does not suffer from radiation damage due to its strong ionic bonds, and the fuel does not have to be removed before all of it was used. Moreover, any fission by-products that are formed can remain in the fuel as well until they too undergo fission and burn up [Hargraves & Moir, 2010; GBCN. Net. 2013].

In LFTR strategy, the reactor will not require any continued uranium input to sustain its nuclear power generation. It will require only roughly one metric tonne of thorium per Gigawatt-year of energy generation. Meanwhile, LWR must be continually replenished with new enriched fissile uranium fuel rods, since they cannot breed their own fuel as do LFTR. LWR will be burned only a very small fraction (3% - 5%) of their own fuel rod's naturally fissile uranium-235 (^{235}U). These reactor designs ignored this is mainly wasteful of uranium, and is unsustainable over the long term. As a result of this solid uranium fuel cycle, LFTR burns just 6 kg of thorium that can produce the same energy as 300 kg of Enriched Uranium (EU) in LWR [GBCN. Net. 2013]. Moreover, 1 tonne of natural thorium produced in LFTR is as much energy as 35 tonne of enriched uranium in conventional reactor [Hargraves & Moir 2010].

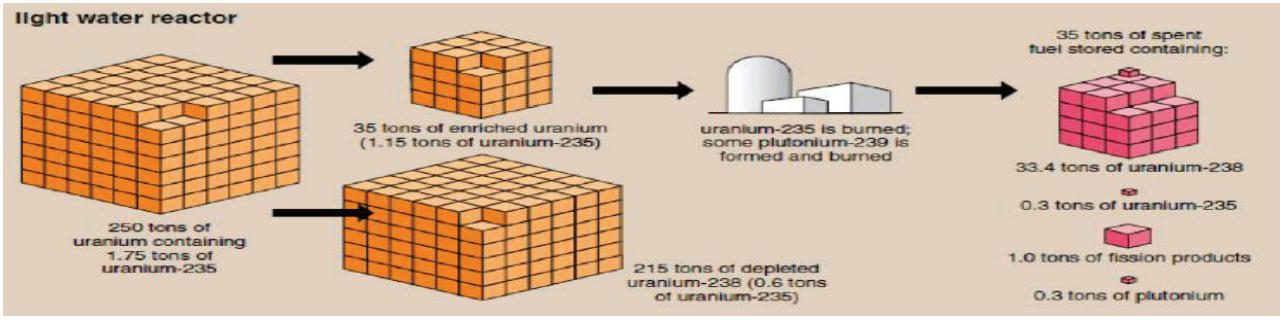
Nuclear Waste

Nuclear reactor produces two kind of radiotoxic waste – fission products such as xenon and long lived transuranic elements such as plutonium. Thorium and uranium reactors produce essentially the same fission products, but they produce a quite different spectrum of actinides. The various isotopes of these elements are the main contributors to the long term radiotoxicity of nuclear waste. In LWR, ^{135}Xe, other noble gases and fission products build up in the solid fuel arrays and the fuel pallets must be changed out before all the available uranium has undergoes fission. However, in a liquid fuel, such wastes can be easily removed during operation. For example, the xenon bubbles out of the fuel as the liquid salt is circulated through the reactor [Hargraves & Moir, 2010]. The LFTR can burn off almost all of its fuel including its own transuranic products. This means that LFTR produced almost no long term waste and very little short term waste, while achieving near total burn up to the fuel.

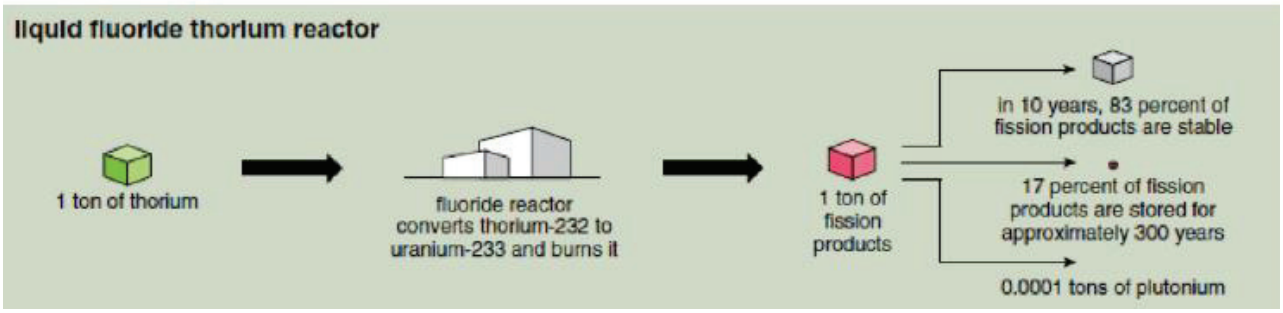
As known, LFTR using fuel salt (LiF-BeF_2-UF_4-Fission product fluorides) is fluorinated, leading to the removal of uranium and volatile hexafluorides from the fuel salt. The volatile fission products shall be recovered and many can be applied in commercial industry instead of being disposed of as waste. The uranium is returned immediately to reconstituted fuel salt. The remaining salt mixture (LiF-BeF_2-nonvolatile fission product fluorides) is then distilled at high temperature. LiF and BeF_2 boil and are recovered and purified, leaving only stable nonvolatile fission product fluorides. These processes were actually demonstrated in the Molten-Salt Reactor Experiment (MSRE). After the extraction of valuable materials such as neodymium and other stable rare earths the amount of nonvolatile fission product fluorides would have been reduced in mass and volume considerably. After that, a stable disposal form suitable for geological disposal without additional conditioning is recommended. The final form represents nearly a theoretical minimum for high level waste volume, having been stripped of the carrier salt (LiF—BeF_2) and actinides as well as all gaseous and volatile hexafluorides fission products [Department of Energy and Climate Change, 2010].

In LWR, uranium fuel cycle start with 250 tonnes of uranium, 35 tonnes of enriched uranium contain 1.15 tonnes of useful ^{235}U. From this, the waste produced is 35 tonnes of fuel containing 33.4 tonnes of ^{238}U, 0.3 tonnes of ^{235}U, 1 tonne of fission product and 0.3 tonnes of plutonium [Hargraves & Moir 2010].

By contrast, in thorium fuel cycle 1 tonne of thorium is used in its entirety and comes out on the end is a tonne of fission products and 0.0001 tonne of plutonium which needs to be stored for a very long time. The fission products produced 83% are stale in only 10 years and 17% in approximately 300 years [Hargraves & Moir 2010; GBCN. Net. 2013]. Figure 1 below showed the comparison between the amounts of raw material needed and waste production for LWR and LFTR [Hargraves & Moir 2010].



(a)



(b)

FIGURE 1. The comparison between the amounts of raw material needed and waste production for (a)LWR and (b) LFTR.

COMPARISON

LFTR which is designed for Generation IV reactor have several differences compared to traditional reactor currently in use. The main difference is the use of fuel cycle. LFTR uses liquid instead of solid fuel, and thorium instead of uranium. This section also will discuss the comparison in term of resource availability, radio-toxicity and nuclear weapon proliferation.

Uranium Vs Thorium Fuel Cycle

Nuclear fuel cycle refers to all activities that occur in the production of nuclear energy. The main difference between LFTR and LWR is LFTR uses fertile ^{232}Th whereas LWR uses fissionable ^{235}U. Figure 2 shows the LWR fuel cycle [Hargraves & Moir 2010]. For LWR, the process of nuclear fuel cycle includes ore mining, purification, enrichment, fuel fabrication, reactor, reprocessing and finally storage and disposal. The uranium ore needs to be mined and then processed (milled) before being usable. Uranium ore is mined by open pit or underground mining methods and the uranium is extracted from the crushed ore in processing plants using chemical methods. This process is known as in situ leaching. This is the first step in nuclear fuel cycle. The feed for mining and milling process is uranium ore and the product is U_3O_8 concentrate, which is called yellowcake. Then, the conversion that refers to the process of purifying the uranium concentrate and converting it to the chemical form required for the next stage is carried out. Uranium hexafluoride UF6 is the predominant product at this stage of the nuclear fuel cycle since it is easily converted to a gas phase for the enrichment stage. For LWR technology, it is impossible to build a LWR with the natural occurrence of ^{235}U, so the ^{235}U content should be increased with a specific process. This process is called enrichment. The feed for this stage is natural UF_6 and the product is enriched UF_6. The other output of the process is the uranium which has lower ^{235}U content than the natural uranium. It is known as enrichment tail or depleted uranium. Enriched uranium in UF_6 form is converted to UO_2 powder to make fuel for LWR technology. This powder then is formed into pellets, sintered to achieve the desired density and ground to the required dimensions. Fuel pellets are loaded into tubes of zircaloy or stainless steel, which are sealed at both ends. These fuel

rods are spaced in fixed parallel arrays to form the reactor fuel assemblies. The whole process is referred to as fuel fabrication. The reactor itself is an irradiator for nuclear fuel. It burns the fuel, produces energy and spent fuel. The spent nuclear fuel still consists of significant amount of fissile material that can be used to produce energy. The considerable amount of ^{235}U is still contained in the spent fuel and there are new fissile nuclides that were produced during normal operation of nuclear reactor such as ^{239}Pu. Some nuclear fuel cycle options consider taking out those fissile material from the spent fuel, refabricating it as fuel and burning in the reactor. Reprocessing process is based on chemical and physical processes to separate the required material from spent nuclear fuel. The feed of this process is spent fuel and the products are reusable material and high level wastes (HLW). The spent fuel, which is not reprocessed, could be stored temporarily for future use or could be stored indefinitely. Spent fuel could be stored in pools [IAEA, 2007].

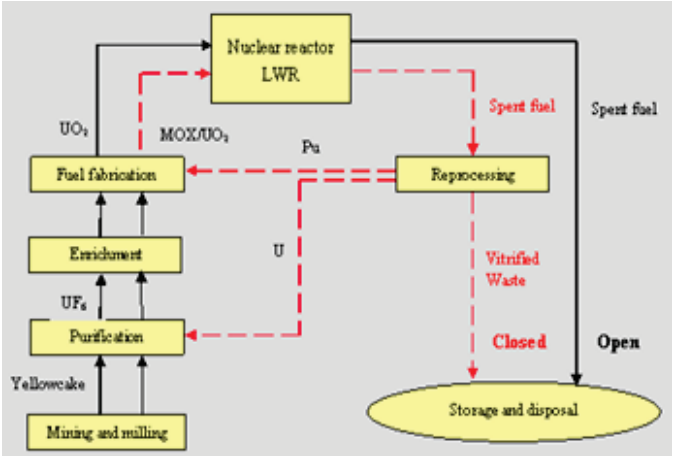


FIGURE 2. Uranium fuel cycle

Meanwhile, Figure 3 shows the thorium fuel cycle in the LFTR. Thorium fuel cycle is a nuclear fuel cycle that uses the naturally abundant isotope of ^{232}Th, as the fertile material. In the reactor, ^{232}Th is transmuted into fissile artificial uranium isotope ^{233}U which is the nuclear fuel. Unlike natural uranium, natural thorium contains only trace amounts of fissile material such as ^{231}Th, which are insufficient to initiate a nuclear chain reaction. Therefore, additional fissile material or another neutrons source is necessary to initiate the fuel cycle. The process of LFTR fuel cycle, which consists of a critical core (orange) containing fissile ^{233}U in a molten fluoride salt, surrounded by a blanket (green) of molten fluoride salt containing ^{232}Th. Excess neutrons produced by fission in the core is absorbed by ^{232}Th in the blanket, generating ^{233}U by transmutation. The ^{233}U and other fission product are recovered by chemical separation and newly bred and recovered ^{233}U is directed to the core, where it sustains the chain reaction [Hargraves & Moir, 2010]. The three essential nuclear reactions started from ^{232}Th is shown below [IAEA, 1962]:

$$^{232}_{90}Th +_{0}n^{1} \rightarrow ^{233}_{90}Th + \gamma\ (neutron\ absroption) \tag{1}$$

$$^{233}_{90}Th \rightarrow ^{1}\beta_{0} + ^{233}_{91}Pa\ (\beta\ decay, \lambda = 22.3\,\mathrm{min}) \tag{2}$$

$$^{233}_{91}Pa \rightarrow ^{-1}\beta_{0} + \ ^{233}_{92}U\ (\beta\ decay, \lambda = 27 days) \tag{3}$$

The nuclear reaction indicated by step 1 shows that neutron absorbed by ^{232}Th will bring about a transmutation to a new isotope namely ^{233}Th and emission of a photon. Logically source for the neutron required for neutron absorption is a power producing fission reactor with fertile ^{232}Th contained in a blanket enveloping the reactor. In step 2, the ^{233}Th isotope emits an electron (beta decay) as it rapidly transmute to protactinium-233 (^{233}Pa). With the half-life only 22.3 minutes over 99.9% of the ^{233}Th is converted into ^{233}Pa in 4 hours. Last step (step 3), the ^{233}Pa isotope itself undergoes a slow transmutation process by beta decay, with half-life of 2 days.

There is a storage requirement or about 10 months for ^{233}Pa to decay to the fissile ^{233}U [J. Juhasz, 2009]. Thus the LFTR fuel cycle entirely eliminates an enormous infrastructure of expensive and complex refinement, manufacturing as well as associated security during its risky transport.

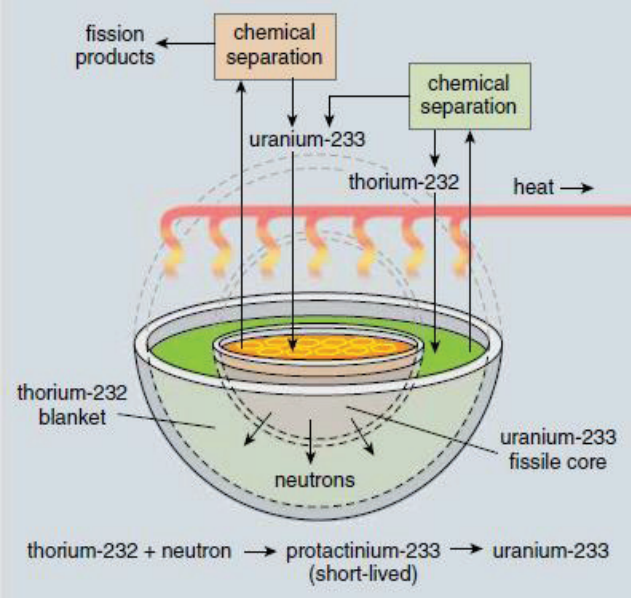


FIGURE 3: Thorium fuel cycle

Resource Availability (Thorium Vs. Uranium)

One of the key aspects in defining the sustainability of any energy source is the availability of fuel resources. Uranium ore makes up 0.00018% of the earth's crust. However, thorium makes up 0.0006% of the Earth's crust. This is means that thorium is three times more abundant than uranium.

Uranium

Uranium was discovered by the German chemist Martin Heinrich Klaproth in 1789. In nature, uranium is found as ^{238}U (99.27%), ^{235}U (0.72%), and a very small amount of ^{234}U (0.005%). Uranium can be found in low level within all rock, soil and water. The average concentration of uranium in Earth's crust is around 2 to 4 part per million (ppm) [IAEA, 2006]. Uranium decays slowly by emitting an alpha particle. The half-life of ^{238}U is about 4.47 billion years and that of ^{235}U is 704 million years making them useful in dating the age of the Earth. It is estimated that 5.5 million tonnes of uranium exists in ore reserves while 3.5 million tonnes are classed as mineral resources [IAEA, 2006]. In 2005, seventeen countries produced concentrated uranium oxides, with Canada (27.9% of world production), Australia (22.8%) and Kazakhstan (10.5%), Russia (8.0%), Namibia (7.5%), Niger (7.4%), Uzbekistan (5.5%), the United States (2.5%), Argentina (2.1%), Ukraine (1.9%) and China (1.7%) also producing significant amounts [World Uranium Production, 1967]. Total identified resources of uranium ore have been estimated by NEA to be sufficient to meet 100 years of supply at 2008 rate of consumption [R Vance, 2010; The Red Book, 2010]. Table 1 below shows the world uranium resources [world nuclear.org, 2014].

Thorium

Thorium is a naturally occurring slightly radioactive metal discovered in 1828 around 160 years after uranium discovered. Thorium discovered by the Swedish chemist on Jakob Berzelius, who named it after Thor, the Nose God of thunder. It is found in small amounts in most rocks and soils. Soil contains an average of around 6 ppm of thorium. The most common source of thorium is the rare earth phosphate mineral, monazite which contains up to 12% thorium phosphate, but 6- 7 % on average. Estimated amount of available thorium resources vary widely. The world thorium resources are estimated to be 5.4 million tonnes over half of which can be found in India, Turkey,

Brazil and Australia [World Association, 2013]. This is enough to power the entire world for tens of thousands of years. Although this is not infinitely sustainable, this is a very long time compared to the roughly 100 years that uranium has to offer. Table 2 shows the estimated world thorium resources [www.world-nuclear.org].

TABLE 1. Reasonably assured uranium resources 2013.

Country	Uranium	
	Tonnes	Percentage (%)
Australia	1,706,100	29
Kazakhstan	679,300	12
Russia	505,900	9
Canada Venezuela	493,900	8
Niger	404,900	7
Namibia	382,800	6
South Africa	338,100	6
Brazil	276,100	5
USA	207, 400	4
China	199,100	4
Mongolia	141,500	2
Ukraine	117,700	2
Uzbekistan	91,300	2
Botswana	68,600	1
Tanzania	58,500	1
Jordan	33,800	1
Other countries	191,500	3
Total	5,902,500	

TABLE 2. Estimated World Thorium Resources

Country	Thorium
	Tonnes
India	846,000
Brazil	632,000
Australia	595,000
USA	595,000
Egypt	380,000
Turkey	374,000
Venezuela	300,000
Canada	172,000
Russia	155,000
South Africa	148,000
China	100,000
Norway	87,000
Greenland	86,000
Finland	60,000
Swedish	50,000
Kazakhstan	50,000
Other countries	1,725,000
Total	6,355,000

Because of the abundant of thorium is higher than uranium, several countries such as India, China and U.S looking for thorium as nuclear fuel. India has abundant quantity of thorium resources contained in the mineral monazite occurring in the beach sand. Atomic Minerals Directorate for Exploration & Research (AMD) has carried out investigations in various areas, thereby establishing sizeable resources of 10.70 million tonnes of monazite which contains 0.963 million tonnes (963,000 tonnes) of thorium oxide (ThO_2) (Indian monazite on an average contains about 9 - 10% of ThO_2). About 846,477 tonnes of thorium metal can be obtained from 0.963 million tonnes of thorium oxide (ThO_2). The entire production process of reactor ready uranium pallets, starting from mining through enrichment. Uranium ore is typically mined as UO_2, UO_3 and U_2O_5. These are collectively referred to as U_3O_8, the most common form of uranium ore [Lam, 2013]. According to World Nuclear Association, it takes 8.9 kg of U_3O_8 to produce 1 kg of enriched uranium. Once mined, the 8.9 kg of ore must be converted into UF_6. The UF_6 produced in the conversion process however is not high enough in ^{235}U concentration to be used in a typical nuclear reactor. Ore is typically mined with a ^{235}U concentration of 0.7% and must be enriched to 5% [Lam, 2013]. However, it should be noted that the external radiation dose is much higher for thorium than uranium leading up to the purification stages because of the decay to thallium-208. Nevertheless, mining of open pit monazite deposits (presently the main source of thorium) is easier than that of most uranium bearing ores, and management of thorium mine tailings is also simpler than in the case of uranium mainly because of the much shorter half live of "thoron" (Rn-220, half-live: 55 sec) than of radon (Rn-222, half-live: 8 days, daughter of Ra-226, 1600 years).

Radiotoxicity

The long term radiotoxicity in LWR spent fuel is dominated by transuranic elements. LWR has uranium fuel with content more than 95% ^{238}U. These reactors normally transmute part of the ^{238}U to ^{239}Pu, a toxic transuranic isotope. The radiotoxicity of spent uranium fuel is dominated for the first 500 years by fission products. After this period the fission products have mostly decayed and the radiotoxicity becomes dominated principally by transuranic elements, particularly plutonium. ^{239}Pu with a half-life of 24,000 years, and is the most common transuranic in spent nuclear fuel from the LWR [Sarah Louise, 2010].

In contrast, the LFTR uses the thorium fuel cycle, which transmutes ^{232}Th to ^{233}U. Because thorium is a lighter element, more neutron captures are required to produce the transuranic elements. ^{233}U has two chances to fission in a LFTR. First as ^{233}U (90% will fission) and then the remaining 10% has another chance as it transmutes to ^{235}U (80% will fission). The fraction of fuel reaching nepthunium-237 (^{237}Np), the most likely transuranic element in LFTR [28]. This is a transuranic production 20 times smaller than LWR, which produce 300 kg of transuranics per GWe-year.

The fabrication of solid fuels containing high-burn up plutonium with ^{238}Pu, americium, and higher actinides is difficult because of the high activity and decay heat associated with these isotopes. In particular, americium presents major challenges because americium oxides are volatile at higher temperatures, which complicate fabrication of fuel pellets, and the radioactive decay of americium generates large quantities of helium in fuel assemblies over time [IAEA, 2004]. No fuel fabrication is required for the LFTR, thus avoiding the fuel fabrication challenges. All of the actinides, including americium fluorides, are highly stable in fluoride salts.

The following radioisotopes are classified as long term radiotoxicity of spent fuel in LWR: Selinium-79 (^{79}Se), zirconium-93 (^{93}Zr), tecnicium-99 (^{99}Tc), palladium-107 (^{107}Pd), tin-126 (^{126}Sn) and cesium-137 (^{137}Cs) [D. Westlén, 2007]. The transuranic elements identified by Westlen that are major contributor to spent fuel radiotoxicity are plutonium, amricium and cerium [D. Westlén, 2007]. The LFTR still produces radioactive fission products in it waste, but they do not last very long – the radiotoxicity of these fission products is dominated by ^{137}Cs and strontium-90 (^{90}Sr). The longer half-life of the isotopes is ^{137}Cs, which is about 30.17 years. So, after 30.17 years of decay the radiotoxicity reduces by itself. 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 LWR waste to start up thorium/uranium fuel generation. This is because the mass number of ^{232}Th is six (6) units less than that of ^{238}U, thus requiring many more neutron captures to transmute thorium up to the first transuranic [Hargraves & Moir, 2010]. The radioactive fission products can similarly be removed from the reactor in days, rather than storing them for years in zirconium-cladded fuel rods of LWRs.

Nuclear Weapon Proliferation

Nuclear weapons proliferation has been prominent in discussion on nuclear power since its earliest days. The nuclear proliferation is a term used to describe the spread of nuclear weapons. The birth of nuclear technology that began with the production of the first weapon using fissionable material such as plutonium produced from nuclear reactor and highly enriched uranium by isotope enrichment. The potential linkage between peaceful use of nuclear energy and the proliferation of nuclear weapons has been a continuing society concern. To ensure the absence of undeclared nuclear material and activities of nuclear material for weapons purposes, an international non-proliferation regime has been developed. Proliferation resistance is defined as the characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material, or misuse of technology, by state intent on acquiring nuclear weapons or other nuclear explosive devices [IAEA, 2004]. Kang and Von Hippel discussed proliferation resistance emphasizing the role of ^{232}U in the thorium fuel cycle [Kang et al, 2001]. The production of ^{232}U produced while making ^{233}U has 2.6 MeV gamma radiations that might makes this fissile material sufficiently resistant to nuclear weapons proliferation. It means that a fuel cycle using ^{232}Th – ^{233}U could be acceptable for a large scale use worldwide. Thorium is more resistant to nuclear weapons proliferation than uranium. Just over 2 new free neutrons are released during fission reaction when ^{233}U absorbs a neutron in the LFTR core. One neutron is used to drive a subsequent fission after being absorbed by another ^{233}U in the blanket solution. A well designed LFTR therefore creates just enough neutrons to generate fuel but not more. If meaningful quantities of ^{233}U are misdirected for no peaceful purposes, the reactor will report the diversion by winding down because of insufficient fissile product being produced in the blanket [Hargraves & Moir, 2009]. Indeed there are 70,000 nuclear weapons in the world and none are based on ^{233}U or the thorium fuel cycle. All of them are based on ^{235}U and ^{239}Pu.

^{239}Pu is a preferred isotope for nuclear weapon design as it has a lower critical mass and easier to produce in large quantities than ^{235}U (must be enriched above 80%). However, the LFTR produce very little plutonium, around 15 kg per Gigawatt-year of electricity. This plutonium is also mostly of Plutonium-238 (^{238}Pu), which makes it unsuitable for fission bombing buildings, due to the high heat and spontaneous neutrons emitted. Furthermore, the plutonium from LFTR can be added to the salt mixture where it is used for energy and broken down into rest-products that are unsuited for use in nuclear weapons [Albert et. Al, 2009]

CONCLUSION

The LFTR has the potential criteria as a new nuclear power to be used in the future. This is because LFTR are safer, cheaper, simple and have more abundant source of nuclear fuel compared to LWR. The most advantages criteria for LFTR are inherent feature safety and lack of nuclear waste produced. Although LFTR does still produce radioactive fission products in its waste, but they do not last very long. Besides that, LFTR which operate at high temperature compared to LWR, enabling more efficient electric/ thermal power conversion technology. Thorium also represents an alternative resource to uranium and has a higher abundance and a different geographic distribution to uranium. The absence of plutonium is in the thorium fuel cycle is claimed to reduce the risk of nuclear weapons proliferation.

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