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To cite this article: Anas Muhamad Pauzi *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **555** 012006

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# Preliminary quantitative feasibility analysis of proposed Thorium-based nuclear reactor

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**Abstract.** In the beginning of the 21<sup>st</sup> century, several research institutions and also private companies had proposed various design of thorium-based nuclear reactor, ranging from solid fuel to molten fuel, fast and thermal neutron spectrum and also various path of waste management. This paper studies 10 of the proposed reactor designs by 10 different organizations, three key aspects analysed quantitatively namely price per kilowatt, safety features and spent fuel managements. Corresponding factors contributing to the key aspects mentioned above were gathered, weighted based on evidence available and analysed using decision matrix. Based on the information collected, preliminary ranking were constructed based on trends between various factors.

## 1. Introduction

### 1.1. Thorium reactor developer of the 21<sup>st</sup> century

Thorium fuel reactor was first developed by the Oak Ridge National Laboratory (ORNL) in 1950s, under the Aircraft Reactor Experimental (ARE) by Alvin Weinberg, then director of ORNL. Thorium fuel was initially proposed in 1960s using the Molten Salt Reactor (MSR) and had proved its reliability for three years until it was shut down due to piping problems. Since then, no thorium fueled reactor was in operation and researches on the thorium fuel was almost non-existence [1]. Van Gosen in 2016 from the US Geological Survey in US had compiled a total of 17 experiments on thorium fuel in reactor from Canada, Germany, India, Japan, the Netherlands, Norway, the Russian Federation, Sweden, Switzerland, the United Kingdom, and the United States [2][3].

Beginning the 21<sup>st</sup> century, thorium fuel reactor had again received wide interest as a promising technology listed in the Generation IV International Forum (GIF) to meet future requirements for nuclear power plant. Institutions and organization from all around the world, both governments and private companies are proposing various reactor designs utilizing thorium as source of reactor fuel [4]. Table 1 below lists most of the organization proposing for future thorium fueled nuclear reactor.



**Table 1:** Organization proposing Thorium-based fuel nuclear reactor design [5].

#	Name of organization	Headquarter	Established	Reactor Name
1	TerraPower [6]	USA	2006	Travelling Wave Reactor/ Molten Chloride Fast Reactor
2	FliBe Energy [7]	USA	2011	Liquid Fluoride Thorium Reactor
3	Thorium Tech Solution Inc [8]	Japan	2011	FUJI Thorium Molten Salt Reactor
4	Transatomic Power [9]	USA	2011	Waste Annihilating Molten Salt Reactor
5	Terrestrial Energy [10]	USA, Canada, UK	2013	Integrated Molten Salt Reactor
6	Copenhagen Atomics [11]	Denmark	2014	CA Waste Burner
7	Moltex Energy [12]	UK	2014	Stable Salt Reactor
8	Elysium Industries [13]	USA	2015	Molten Chloride Salt Fast Reactor
9	Seaborg Technologies [14]	Denmark	2015	Seaborg Wasteburner Molten Salt Reactor
10	ThorCon International [15]	USA, Indonesia	2016	Molten Salt Reactor

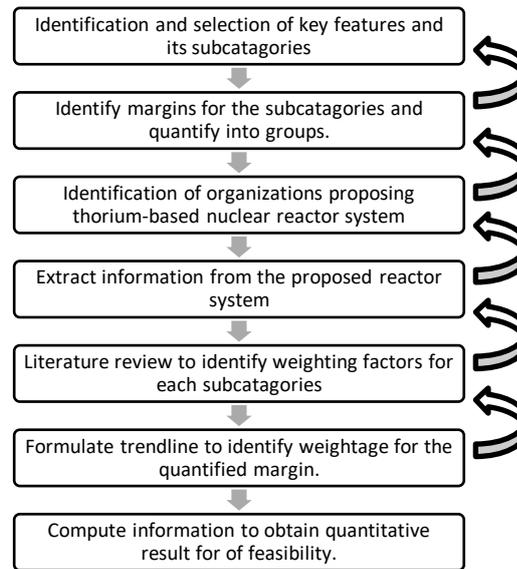
From Table 1 above, all of the organizations proposing future thorium-based nuclear reactor are private companies and mostly are based in the United States. None of the major or current nuclear power plant manufacturer had yet to propose any conceptual design for the thorium fueled nuclear reactor.

### 1.2. Nuclear Reactor Technology Assessment

Quantitative tools for nuclear reactor technology assessment were developed all around the world as many nations are starting to reintroduce new build nuclear reactor after a long pause since Chernobyl and also new countries are starting to embark in nuclear power to meet the demand of clean energy. The IAEA had introduced the Reactor Technology Assessment (RTA) tool for basic guideline [16]. Harper Mark in 2015 had compiled key features for technology assessment in as such he sorted out features that have high priorities, where the high priority criterion could be grouped into three main areas which are economics, safety and waste management [17]. These three groups are also part of the goals for future reactor system as listed in the Generation IV International Forum (GIF) [18]. Meanwhile, proliferation resistance and physical protection were considered requirement for all future reactor systems, hence, not a differentiator for assessing feasibility [17]. Economics, safety and waste management were chosen as the top priority for this assessment, where information on these 3 objectives were gathered based on journal papers published by the listed organizations or information made available officially on their websites.

## 2. Methodology

An overview of the flow chart to achieve this assessment is shown in Figure 1. This study requires a formulation of quantitative values for each criteria and an intelligent estimation based on available information. The process would be iterative where additional information would be included and thus affect the weightage values assigned. The output of this process is to automatically generate feasibilities ranking for future thorium reactor design provided basic input information.



**Figure 1.** Methodology for quantitative feasibility study for future thorium based nuclear system.

### 2.1. Price of electricity

Assessing the expected price per kilowatt for a technology at the conceptual early stage of its readiness level would be very speculative as it is prone to high level of uncertainties [19]. With available information, a preliminary ranking was formed.

The total cost per kilowatt are broken down into categories which are reactor size, fuel type, fuel state, neutron spectrum and type of working fluid. The weightage of each categories were initially assigned equally.

#### 2.1.1. Price: Reactor Size

Smaller reactor size are less economical compared to larger unit due to economy of scale, inefficient utilization of power plant infrastructure, transmission grid and management, hence, most design of small reactor would suggest to be constructed in multiple unit [20]. A simple analysis on the announced construction cost and its corresponding power station output is gathered in Table 2.

**Table 2.** Construction cost and power of new nuclear power plant [21][22].

Nuclear Power Station	Country	Construction Cost, C (Billion USD)	Capacity, P (MW)	Cost, C/Capacity, P (Bil. USD/MW)
Barakah	United Arab Emirates (UAE)	24.4	5380	4.535
Akkuyu	Turkey	20	4800	4.167
Shidao Bay	China	15.7	3400	4.618
Hinkley Point C	United Kingdom	20.3	3260	6.227
Ruppur	Bangladesh	13.5	2160	6.250

Based on information from Table 2, a trend line was developed to analyse the weightage for price per power produced based on the construction cost as in Equation 1. At a correlation of 80%, the trend showed linear line, where it would be economical to have larger amount of power output in a power station, either by multiple units or larger reactor size.

$$\text{Weightage-Plant Size, } W_s = \text{Construction cost per Power, } C/P_R = -0.0006P_i + 7.5224 \quad (1)$$

### 2.1.2. Price: Neutron Spectrum.

Further analysis on the construction cost, the difference between the thorium reactor operating in fast and thermal neutron spectrum were compiled and weightage based on neutron spectrum,  $W_{NS}$  were assigned based on the average values as shown in **Table 3**.  $W_{NS}$  is inversely proportional to the average cost per megawatt power.

**Table 3.** Construction cost and power output for fast and thermal reactors [22].

Neutron Spectrum	Reactor name	Capital cost (Billion USD)	MW	Cost (mil) /MW	Country	Average Cost (Bil) /MW	Weightage, $W_{NS}$
Fast	BN-1200	6	1220	4.918	Japan		
	BN-600 reactor	4.957	600	8.262	Russia	8.178	<0.5>
	PFBR	5.677	500	11.354	India		
Thermal	Barakah APR-1400	24.4	5380	4.535	UAE		
	Ruppor VVER 1200	13.5	2160	6.250	Bangladesh	4.984	<1.0>
	Akuyyu VVER-1200	20	4800	4.167	Turkey		

2.1.3. Price: Fuel State and Fuel Type. There are two state of fuel used in a thorium fuelled reactor which are solid fuel and molten fuel. Molten fuel are technically easier to manufacture since fuel conversion, enrichment and fabrication process can be skipped and uranium hexafluoride could be directly mixed and used inside the reactor. The process mentioned consists of 57% of the total cost of fuel preparation [24][25]. Weightage on the price per kilowatt effect as proportion to the total cost as shown in Table 4.

Small number of thorium based reactor were designed to be able to operate without requiring the use of enriched uranium or minimal amount of enriched uranium during its initial start-up of the reactor. Hence, the weightage is assigned based on the ratio of the difference in the cost of natural uranium with and without enrichment process as shown in Table 4.

**Table 4.** Fuel state and cost fraction [24][25].

Processes	Cost fraction	Fuel state- <Weightage, $W_{FS}$ >	Fuel type <Weightage, $W_{FT}$ >
Uranium mining	43%	Molten <1.0>	Natural Uranium
Conversion	8%		Enriched Uranium
Fuel fabrication	22%	Solid <0.43>	<1.0>
Enrichment	27%		<0.65>

2.1.4. Price: Working Fluid. All proposed reactor design utilizes either molten salt or liquid metal as its working fluid, either as its coolant or molten with fuel mixture. Price of the working fluid were estimated by comparing bulk price for the elements contained within the working fluid from popular online chemical elements shopping which are *Chemical Book* and *Chemicool* [25-27].

Table 5 shows the cost of the elements in the work fluid and the corresponding weightage,  $W_{LT}$ . It shows that molten salt are more expensive than liquid metal. Table 5 shows the cost of the elements in the work fluid and the corresponding weightage,  $W_{LT}$ . It shows that molten salt are more expensive than liquid metal.

**Table 5.** Type of working fluid and cost [26][27].

Working Fluid Type	Fluid name	Mixture	Composition (%)	USD/1g	USD/1g	Average USD/1g - <Weightage, $W_{LT}$ >
Salt	FLiBe	LiF (98.5%)	66.7%	0.516	0.68	0.51 <1.0>
		BeF (99%)	33.3%	1		
	FLiNaK	LiF (98.5%)	46.5%	0.516	0.34	
		NaF (99%)	11.5%	0.0628		
		KF (99%)	42.0%	0.225		
Metal	Lead-Bismuth Eutectic (LBE)	Lead	44.5%	0.0245	0.23	
		Bismuth	55.5%	0.39		
	Liquid metallic Sodium (Na)	Na-23	100.0%	0.25	0.25	0.24 <0.5>

## 2.2. Reactor safety

Safety of the proposed thorium reactors focusses on the molten state of fuel, since most of the proposed reactor suggested molten state because of the significant safety advantages compared to solid state fuel reactors such as its low or atmospheric operating pressure, high boiling temperature, large negative temperature reaction coefficient, continuous removal of gaseous fission product that minimize chemical reprocessing and various inherit passive safety features [1][28].

Tritium,  $^3\text{H}$ , commonly written as T which is a radionuclide of hydrogen, are produced when neutron interact with Lithium-Beryllium Fluoride (FLiBe) forming Tritium Fluoride, TF. This causes corrosion and embrittlement on the structural metal. In case of an accident of core exposure, Tritium may diffuse to the environment and dilute in air to form *Tritiated water* (HTO) which could easily be inhaled and cause serious internal exposure [28]. Comparing with PWR, the tritium production rate of MSR is about 200 times higher; hence, tritium management becomes one of the most critical issues for using molten salt as a working fluid [29].

As an alternative to molten salt as working fluid, thorium reactors can apply liquid metal such as Lead-Bismuth Eutectic (LBE) which would have higher risk of corrosion on structural metal and may also face problem of solidification when the reactor operates at low temperature. Furthermore, LBE coolant reactors would require extra precautions of alpha contaminants due to Polonium-210 build-up with neutron flux [30].

Table 6 summarizes some of the safety criteria with the lower and upper weightage,  $W_s$ , with preliminary assumed as 0.5 and 1.0. Further analysis would provide more input on the risk and hazard mitigation related to the safety criteria.

**Table 6.** Safety criteria of Thorium-based reactor.

Criteria	Description	Weightage, $W_s$	
		Lower <0.5>	Upper <1.0>
Number of loops	Adding more shielding later	2 Loops	3 Loops
Working fluid	Both liquid metal and molten salt have their pros and cons, but overall molten salt shows better safety criteria	Liquid metal	Molten salt
Reduced number of moving parts	Some reactor design claim to operate fully via natural convection and does not require any online fuel management	No moving parts	Moving parts in fuel management and pump

### 2.3. Spent fuel management

The effective management of spent fuel is another important issue that must be taken into account when using Th-based fuel for nuclear reactor operations. In general, there are four main concerns in dealing with spent nuclear fuels from Th-based reactor namely; decay heat, spontaneous neutron emission rates and radiotoxicities (gamma-ray) per discharge assembly, as well as the volume of spent nuclear fuel [31]. It is advisable that the spent fuel is stored in waste-form package, or wet/dry storage for long period due to high amount of decay heat. Apart from that, stronger shielding measurement with the help of remote operation is necessary in order to contain the gamma ray production. In this study, in spite of the issues regarding spent fuel management, none of the working organizations seems to address them. This is possible because these organizations claimed that very small amount of spent fuel production is produced on Th-fueled compared to U-fueled reactor, hence only small repositories of spent fuel are required. Some even believed that no long term storage is even needed due to the short decay period, for example, SWaB reactor by Seaborg Technologies declared that their technology reduce the year of storage to 20-30 years [14]. The ThornCon Power on the other hand claimed that their technology does not require to separate the spent-fuel cooling and storage system. The decay heat is reduced to 0.25% of the original (80kW) before being pumped the old fuelsalt to shipping casks [15].

### 3. Conclusion

Overall, preliminary quantitative feasibility study were performed on proposed Thorium based nuclear reactor involving 3 main criteria, which are economics, safety and waste management. Ten companies were studied where some basic differences such as size, working fluid, neutron spectrum, number of loops were tabulated. Quantitative values were predicted with publically available evidence on the analysis of its advantages and disadvantages. More study on the safety need to be performed to provide reliable quantitative feasibly. Much of the challenges regarding spent fuel management are not currently addressed by all the proposed design.

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