Nuclear Engineering and Technology 51 (2019) 631–640

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Economic analysis of thorium extraction from monazite

Ahmad Hayaton Jamely Mohd Salehuddin [a], Aznan Fazli Ismail [a, b, *],
Che Nor Aniza Che Zainul Bahri [a], Eli Syafiqah Aziman [a]

[a] *Nuclear Science Program, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia*
[b] *Centre for Frontier Science, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia*

ARTICLE INFO

Article history:
Received 5 July 2018
Received in revised form
31 October 2018
Accepted 9 November 2018
Available online 12 November 2018

Keywords:
ThO_2
Extraction plant
Monazite
Cost analysis
Direct cost
Indirect cost
Capital investment

ABSTRACT

Thorium (^{232}Th) is four times more abundant than uranium in nature and has become a new important source of energy in the future. This is due to the ability of thorium to undergo the bombardment of neutron to produce uranium-233 (^{233}U). The aim of this study is to investigate the production cost of thorium oxide (ThO_2) resulted from the thorium extraction process. Four main parameters were studied which include raw material and chemical cost, total capital investment, direct cost and indirect cost. These parameters were justified to obtain the final production cost for the thorium extraction process. The result showed that the raw material costs were $63,126.00 –$104,120.77 (0.5 ton), $126,252.00 – $178,241.53 (1.0 ton), and $1,262,520.00 –$1,782,415.33 (10.0 tons). The total installed equipment and total cost investment were estimated to be approximately $11,542,984.10 and $13,274,431.715 respectively. Hence, the total costs for producing 1 kg ThO_2were $6829.79– $6911.78, $3540.95 – $3592.94, and $501.18 – $553.17 for 0.5, 1.0, and 10.0 tons respectively. The result concluded that with higher mass production, the cost of 1 kg ThO_2 would be reduced which in this scenario, the lowest production cost was $501.18 kg^{-1}– $553.17 kg^{-1} for 10.0 tons of ThO_2 production.

1. Introduction

Thorium is known as a naturally occurring radioactive material (NORM) which is four times more abundant than uranium in nature. Normally, thorium isotope exists as thorium-232 (^{232}Th), and its half-life is 14.05 billion years. ^{232}Th is a fertile material which does not undergo fission reaction by itself. However, the reaction of ^{232}Th with neutron will produce ^{233}U which is a fissile material by two beta decays (Eq. (1)). As a result, thorium can be utilized as an alternative nuclear fuel to replace uranium [1,2]. The conventional uranium resources were reported to available about 80 years before runs out [3], or unless other uranium resources such as uranium from seawater become economically extractable.

$$^{232}Th + {}^{1}n \rightarrow {}^{233}Th + \beta \rightarrow {}^{233}Pa + \beta \rightarrow {}^{233}U \qquad (1)$$

There are several types of reactors where ThO_2 can be used as a nuclear fuel such as heavy water reactors, high-temperature gas-cooled reactors, boiling water reactors, pressurized water reactors, fast neutron reactors, and molten salt reactors [4]. Thorium was suggested as a future nuclear fuel in Generation-IV nuclear reactor in the Generation-IV International Forum (GIF-IV). One of the recommended thorium reactors is Very High Temperature Reactor (VHTR) which uses thorium oxide (ThO_2) as fuel [5]. As for nuclear fuel, ThO_2 has more advantages compared to uranium such as being relatively inert and having lower thermal expansion than UO_2. Fission gas release from ThO_2 nuclear fuel pellets is considerably lower than that from UO_2 which results in lower nuclear byproduct as well as a lower hazard of nuclear accidents in thorium-based nuclear reactors. In particular, its high thermal conductivity makes ThO_2 a better fuel for nuclear reactors since thermal transport is a critical issue that is directly related to the lifetime of nuclear fuels [4].

The main source of thorium is mineral phosphate monazite, which contains about 3.1 %–11.34% of ThO_2 which has the highest percentage of thorium compared to other minerals [6]. However, monazite also contains a high amount of rare earth elements which contribute about 54 %–60% and a small amount of uranium, ranging from 0.2% to 0.4% [7]. Many research has been conducted for the last 69 years to obtain high purity ThO_2. Generally, two main methods are commercially applied to separate thorium from

---

[*] Corresponding author. Nuclear Science Program, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia.
E-mail address: aznan@ukm.edu.my (A.F. Ismail).

https://doi.org/10.1016/j.net.2018.11.005

mineral monazite that is through either acid digestion or leaching process. In a typical acid digestion process, monazite is cracked using sulfuric acid at 230 °C for 4 h. The process is followed by a selective precipitation process using ammonium hydroxide (NH_4OH), sodium hydroxide (NaOH), and hydrogen peroxide (H_2O_2) to separate thorium from rare earth elements (REE) and uranium [8,9]. According to Bahri et al. [7], a total of 97.68% thorium was able to be separated at the pH of 1.05–1.84.

Furthermore, thorium has also been purified using several industrial processes such as solvent extraction, ion exchange, and direct precipitation [10]. Amongst all, solvent extraction is the most powerful method as it is safe, clean, and cheap, which meets the need of present and future generations. Some studies have proven that through this method, thorium has been successfully extracted with more than 98% purity. Research conducted by Al-Areqi W. M. et al. [6] using TBP and nitric acid (HNO_3) successfully recovered thorium up to 91.8% purity.

However, in all these previous studies, there was no further discussion on the economic analysis of the thorium extraction process. Therefore, whether the cost of thorium oxide production is cost-effective or vice versa remains questionable. In this cost assumption study, there are some factors that need to be considered to ensure that this technique offers a lower cost compared with other technique such as raw material cost, equipment cost, and total plant cost. The aim of this study is to estimate the production cost of thorium oxide from mineral monazite.

2. Method and materials

In this study, the costs of raw material, chemicals, and equipment were collected from various sources and the total production costs were given in a range from the minimum to the maximum. The production cost of ThO_2 in this study was estimated with a nominal error of ±30%. It is imperative to estimate the economic feasibility of a project prior to investing significant funds for piloting, marketing, land surveys and other related to a project [11]. Therefore, in order to estimate the production cost of ThO_2, a cost comparison was made based on mass production of 0.5, 1.0, and 10 tons of ThO_2. In addition, it is necessary to carry out a refined design to determine the equipment used as well to estimate the actual equipment cost. The total cost of the investment was determined based on the cost of the installed equipment. Fig. 1 shows the flow diagram of ThO_2 production from mineral monazite.

2.1. Thorium extraction process (based on a laboratory scale)

The extraction of thorium involved four stages: digestion, separation, purification, and calcination. Digestion was done by leached the monazite with hot concentrated sulfuric acid (98% H_2SO_4) at 230 °C for 4 h as shown in Eq. (2) [7,12–14]. Then, thorium was separated from rare earth elements and uranium by selective precipitation using 13.4 M NH_4OH at pH 1.05–1.84 (Eq. (3)) [12,15]. Furthermore, the purification of thorium from other metals and rare earth elements was achieved through a solvent extraction process using tributyl phosphate (TBP) in kerosene (Eq. (4) & Eq. (5)) [12]. Thorium was then sent to a precipitator where it was converted into insoluble thorium oxalate, $Th(C_2O_4)_2$. The $Th(C_2O_4)_2$ was heated at 1000 °C in a furnace and was subsequently converted into ThO_2 as the final product (Eq. (6) & Eq. (7)) [11].

$$Th(PO_4)_4 + 6H_2SO_4 \rightarrow 3Th(SO_4)_2 + 4H_3PO_4 \quad (2)$$

$$3Th(SO_4)_2 + 4NH_4OH \rightarrow Th(OH)_4 + 2(NH_4)_2SO_4 \quad (3)$$

$$Th(NO_3)_4 + TBP \rightarrow Th(NO_3)_4.TBP \quad (4)$$

$$Th(NO_3)_4.TBP + H_2O \rightarrow Th(NO_3)_4 + TBP.H_2O \quad (5)$$

$$Th(NO_3)_4 + 2C_2H_2O_4 \rightarrow Th(C_2O_4)_2.4H_2O + 4HNO_3 \quad (6)$$

$$Th(C_2O_4)_2.4H_2O \rightarrow_{-} ThO_2 + 2CO_2 + 2CO + 4H_2O \quad (7)$$

Designing the pollution control system require auxiliary equipment in term of waste treatment facilities, pollution control, and other related equipment [16]. The cost of the auxiliary facilities was estimated to be 30% of the equipment cost, as given in Appendix A. The pollution control design will rely on the types of residue (pollutant) to be controlled [17].

Several types of waste stream (gas, liquid and, solid residues) are expected to be produced during the extraction, separation and refining process [18]. Some type of residue might have economic value depending on the residual treatment. For example, the non-thorium metal (rare-earth elements) in the liquid residue (Appendix B) can be further purified to produce high-grade of rare earth elements based on the industrial requirement. In addition to that, the phosphate yielded during the leaching process is potentially be used for agriculture application [18,19]. For the radiological safety concern, the International Atomic Energy Agency (IAEA) recommended 20 mSv $y^{-1}$for the workers [20]. However, Al-Areqi et al. [15] reported that the dose received by the workers might exceed the recommended dose limit depending on the processing stage. Therefore, the extraction plant activities should be regulated according to the regulation set by the authority.

2.2. Raw material and chemicals cost estimation

The raw material used to produce ThO_2 in this study was monazite. Meanwhile, the chemicals used in the whole process were 98% H_2SO_4, 37% NH_4OH, 70% HNO_3, $C_2H_2O_4{\cdot}2H_2O$, TBP, and kerosene. The estimated production cost of ThO_2 was based on the laboratory scale data. Appendix C shows the mass or volume of raw materials and chemicals consumed in the thorium extraction process per kilogram. The mass or volume of monazite and chemicals at a large scale were calculated using Eq. (8) and Eq. (9):

$$m_n = \frac{T_r}{T_e} \quad (8)$$

$$Q_{n,1} = m_{n,1}\, XS_{LS} \quad (9)$$

where m_n is the mass coefficient while T_r and T_e are desired mass for tested and experimental mass in kg respectively. Meanwhile, Q_n and S_{LS} are the total quantity of the desired mass and raw material in laboratory scale, respectively.

2.3. Equipment cost estimation

In this process, the equipment involved were leaching vessel, agitator, solvent extractor, stripper, vacuum filter, precipitator, storage, pump, and calcination kiln. The size and the capital cost of the equipment were determined based on mass balance and Ulrich's method [16] (Eq. (10)), respectively as follows:

$$C_p = C_o \times F_{bm} \times \left(\frac{I_p}{I_o}\right) \quad (10)$$

where C_p, C_o, I_p, I_o and F_{bm} are cost at the present time, cost at time

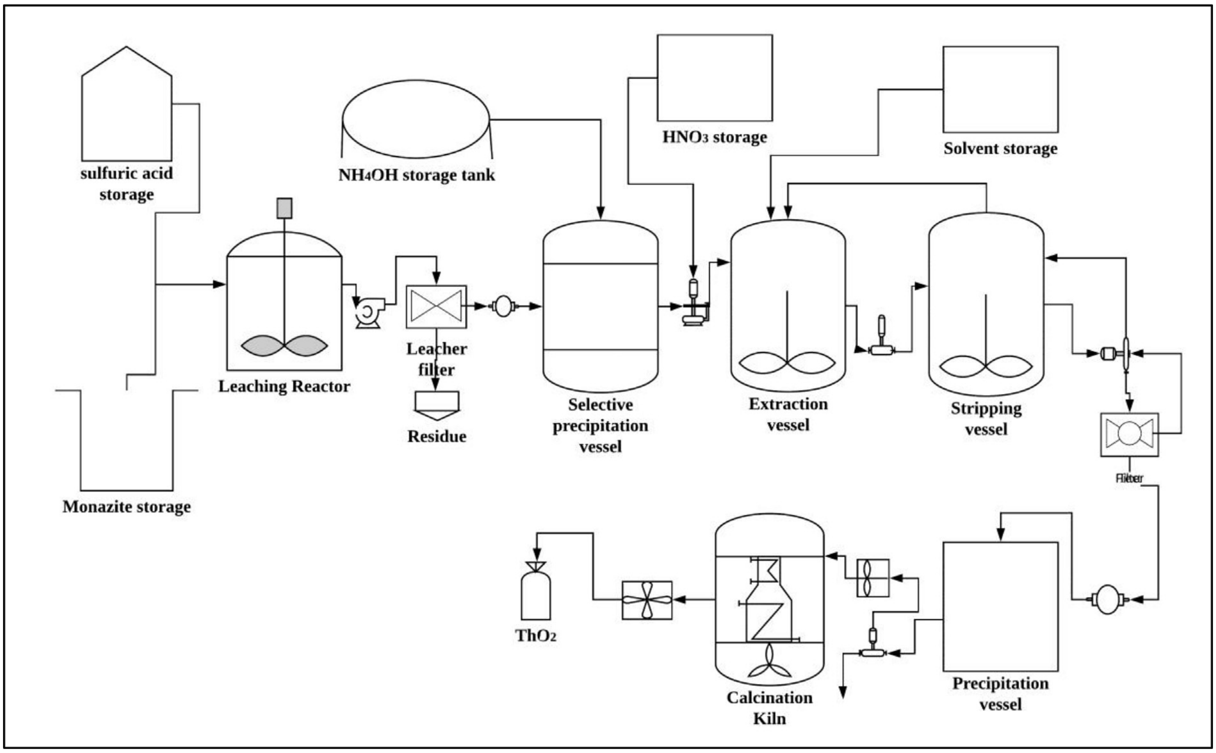

Fig. 1. Thorium extraction process flow diagram from monazite to thorium dioxide ThO_2.

t, chemical engineering (CE) plant cost index at the present time (2018: 607.2), and CE plant cost index at time t (2002: 400) and bare modul factor (following Ulrich method) respectively. The detail of equipment size and power is given in Appendix D.

2.4. Processing cost estimation

The processing cost involved in producing ThO_2 was classified into four categories which were a fixed capital cost, raw material cost, manufacturing cost and total cost production. The accounting methods outlined by Ulrich [16] were applied in this cost analysis study. The method required to first determine the actual capital of each piece of equipment as shown in Appendix A. The following step required the sum of the equipment capital The amount of fixed capital for a non-grassroots plant was related to the capital contingency and fee, which is given by the following equation:

$$C_c + C_F = 0.18 \times C_{BM} \tag{11}$$

Where C_C, C_F and C_{BM} are the associated capital of contingencies and fees and total equipment capital.

Moreover, for operating labor is usually the second largest direct expense item in the manufacturing expense. For labor calculation, almost all plants operate on a shift-work basis, with typically 4.8 operators per shift position with five 8-h shifts a week. This gives a four-shift rotation with allowance for weekends, vacations, holidays, and some use of overtime. Eq. (12) was used to calculate the operating labor by multiplying the number of operators per shift with 4.8 operators per shift:

$$N_{OP} = \left(6.29 + 31.7^{P} + 0.23 N_{NP}\right)^{0.5} \tag{12}$$

where N_{OP}, P, and N_{np} are the number of operators per shift, number of processing steps involving the handling of particulate solid (i.e., distribution, particulate size control, and particulate removal), and number of non-particulate processing steps (compressors, towers, reactors, heaters, and exchangers) respectively [21]. The operator and supervisor salary was based on the average Malaysia labor and supervisor wage [22] as shown in Table 1.

After the determination of the total capital cost, direct, and indirect cost, another important part is the estimation of costs for the plant operation and selling the products. These costs can be grouped under the general heading of total production cost. Generally, the total production cost is divided into two categories, i.e., manufacturing costs and general expenses. The manufacturing cost includes direct and indirect production cost, general expenses, and annual depreciation. Direct production cost includes raw material cost, utilities cost, operating labor cost, maintenance, and others. Meanwhile, indirect cost involves are depreciation, taxes, and insurance as shown in Table 2. Eq. (13) was used to calculate the total production cost:

$$C_T = C_{raw} + C_m \tag{13}$$

Where C_T, C_{raw}, and C_m, are the total cost, the cost of raw material, and the manufacturing cost respectively.

The economic evaluation was conducted in the preliminary stage of the plant design which includes the calculation of raw material, equipment, and processing cost estimation to determine the cost for total mass production of thorium extraction process. As mentioned before, different mass productions were tested for the cost comparison purpose. The pilot plant was assumed to be processing for 24/7, hence it is a continuous process. However, this research focused on the economic value for a single batch cycle, which requires eight hours to process each one batch.

Table 1
Utilities involved in thorium extraction process.

Utilities	Estimation Cost
Operator and supervisor salary	Labor: \$ 4753.07/year (\$ 396.09/month) Supervisor:\$ 8556.68/year (\$ 713.07/month)
Electricity cost	\$ 0.053/kWh
Process water (per 35 m^{-3} = \$ 0.55)	\$ 0.016 m^{-3}
Steam	\$ 0.012 kg^{-1}

*Average operator salary were obtained from average wage for salary in Malaysia [22].
* Electricity and processed water cost were estimated through general industrial tariff provided by Malaysian Electrical Utilities (Tenaga Nasional Berhad, TNB) and Malaysian Water Utilities (Syarikat Bekalan Air Selangor Sdn Bhd, SYABAS), respectively.

Table 2
Distribution factor for calculation of direct and indirect cost estimation.

Manufacturing cost	*Cost Distribution
Direct Cost	
Maintenance and repairs	6% of fixed capital
Operating supplies	15% of Maintenance and repairs
Laboratory charges	5% of Total expense
Payroll	15% of Labor and Supervision
Indirect Cost	
Overhead	40% of Labor, Supervision and Maintenance
Insurance	1.5% of fixed capital
tax rate	1.5% of fixed capital

3. Result and discussion

3.1. Raw material and chemical cost estimation

The cost of raw material and chemicals were shown in Appendix C, while, the mass consumption of raw material and chemicals were calculated based on the laboratory scale as shown in Appendix E. The present cost of monazite ranges from \$1680 to \$1900 ton^{-1}. Meanwhile, other chemicals used such as sulfuric acid, ammonium hydroxide, tributyl phosphate, kerosene and nitric acid costs range from \$188–\$240 ton^{-1}, \$200–\$300 ton^{-1}, \$1000–\$1500 ton^{-1}, \$200–\$250 ton^{-1} and \$200–\$220 ton^{-1} respectively. Table 3 shows the cost of raw material and chemicals for the thorium extraction process. Based on the result, the total consumption of 0.5, 1.0, and 10.0 tons of ThO_2 range from \$63,126.00–\$104,120.77, \$126,252.00–\$178,241.53 and \$1,262,520.00–\$1,782,415.33 respectively. Monazite shows the highest mass consumption in thorium extraction process. Based on the cost consumption, production of ThO_2 is highly influenced by the oxalation process. The oxalic acid consumed are 98.5–1970.0 kg h^{-1} and it produces only about 4.67% thorium oxalate ($Th(C_2O_4)_2$) as shown in Appendix F. Thus, this shows that oxalic acid is the second highest cost contributor in the production of ThO_2, where the cost for all productions ranges from \$8403.33–\$294,116.67.

3.2. Equipment cost and capital cost estimation

The details for the equipment cost used in the thorium extraction process is shown in Appendix A. There are five main pieces of equipment in the plant which are a reactor, separator, process vessel, calciner and pump (Fig. 2). Meanwhile, the auxiliary facility were assumed to be the other facilities such as the waste disposal, pollution control and other related equipment. The result indicates that the total cost of the equipment is \$ 9,782,189.92. The result also shows that the highest equipment cost is the reactor (\$ 4,121,370.00) while the lowest cost is the calciner (\$ 745 467.03). Appendix G shows the cost for a capital investment of thorium extraction in the plant scale. Capital investment cost includes the fixed cost (C_{FC}) and the working capital (C_{WC}). The fixed cost is calculated based on the total bare module cost by including the capital contingency and fee (Eq. (11)). The result shows that the fixed cost and the total capital investments are \$11, 542, 984.10 and \$ 13,274,431.715 respectively.

Furthermore, Appendix G shows the manufacturing cost summary for thorium extraction plant. The result presented in the table is based on the mass production per kilogram, which are 0.5, 1.0, and 10 tons kg^{-1}. Fig. 3 shows the pie chart for direct and indirect manufacturing cost distribution for 0.5, 1.0, and 10.0 tons of ThO_2. The results indicate that the cost for maintenance, supplies, laboratory and payroll charge are inversely proportional to the mass production that range from \$1385.00–\$69.26 kg^{-1}, \$207.75–\$10.39 kg^{-1}, \$18.30–\$1.78 kg^{-1} and \$21.05-\$2.05 kg^{-1} respectively. The labor and supervision costs are estimated based on the size of mass production. 50–107 labors are assumed to process 0.5, 1.0, and 10.0 tons of ThO_2. It shows that the costs needed for labor and supervisor to produce 1 kg ThO_2 are approximately \$140.31 h^{-1}, \$102.04 h^{-1}, and \$13.65 h^{-1}.

The total of direct manufacturing costs for 0.5, 1.0, and 10.0 tons/

Table 3
Cost assumption for raw material and chemicals at 0.5, 1.0, and 10.0 tons.

Material/Chemical	Cost \$/tons					
	0.5 tons		1.0 tons		10.0 tons	
	min	max	min	max	min	max
Monazite	14,000.00	15,833.33	28,000.00	31,666.67	280,000.00	316,666.67
H_2SO_4	3133.33	4000.00	6266.67	8000.00	62,666.67	80,000.00
NH_4OH	8000.00	12,000.00	16,000.00	24,000.00	160,000.00	240,000.00
Nitric acid	1589.33	1748.27	3178.67	3496.53	31,786.67	34,965.33
TBP	23,333.33	50,000.00	46,666.67	70,000.00	466,666.67	700,000.00
Kerosene	4666.67	5833.33	9333.33	11,666.67	93,333.33	116,666.67
$C_2H_2O_4$	8403.33	14,705.83	16,806.67	29,411.67	168,066.67	294,116.67
Total (\$)	63,126.00	104,120.77	126,252.00	178,241.53	1,262,520.00	1,782,415.33

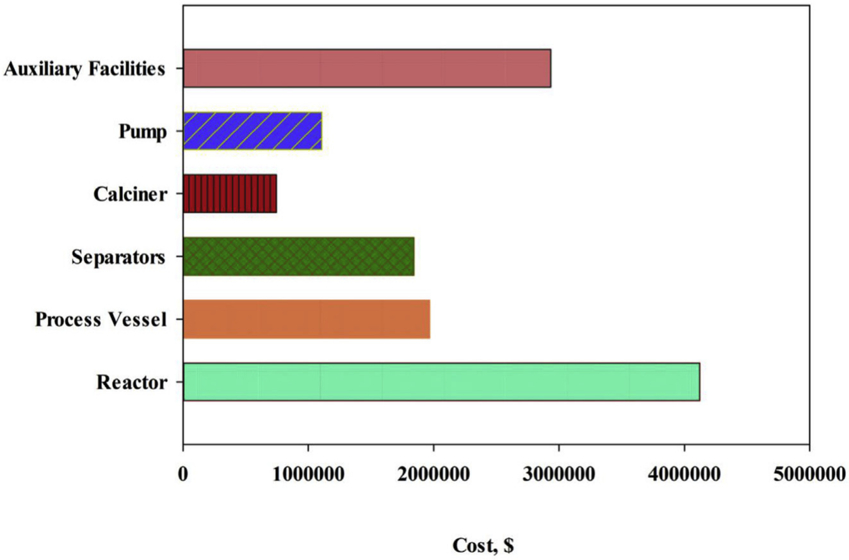

Fig. 2. Equipment cost Distribution.

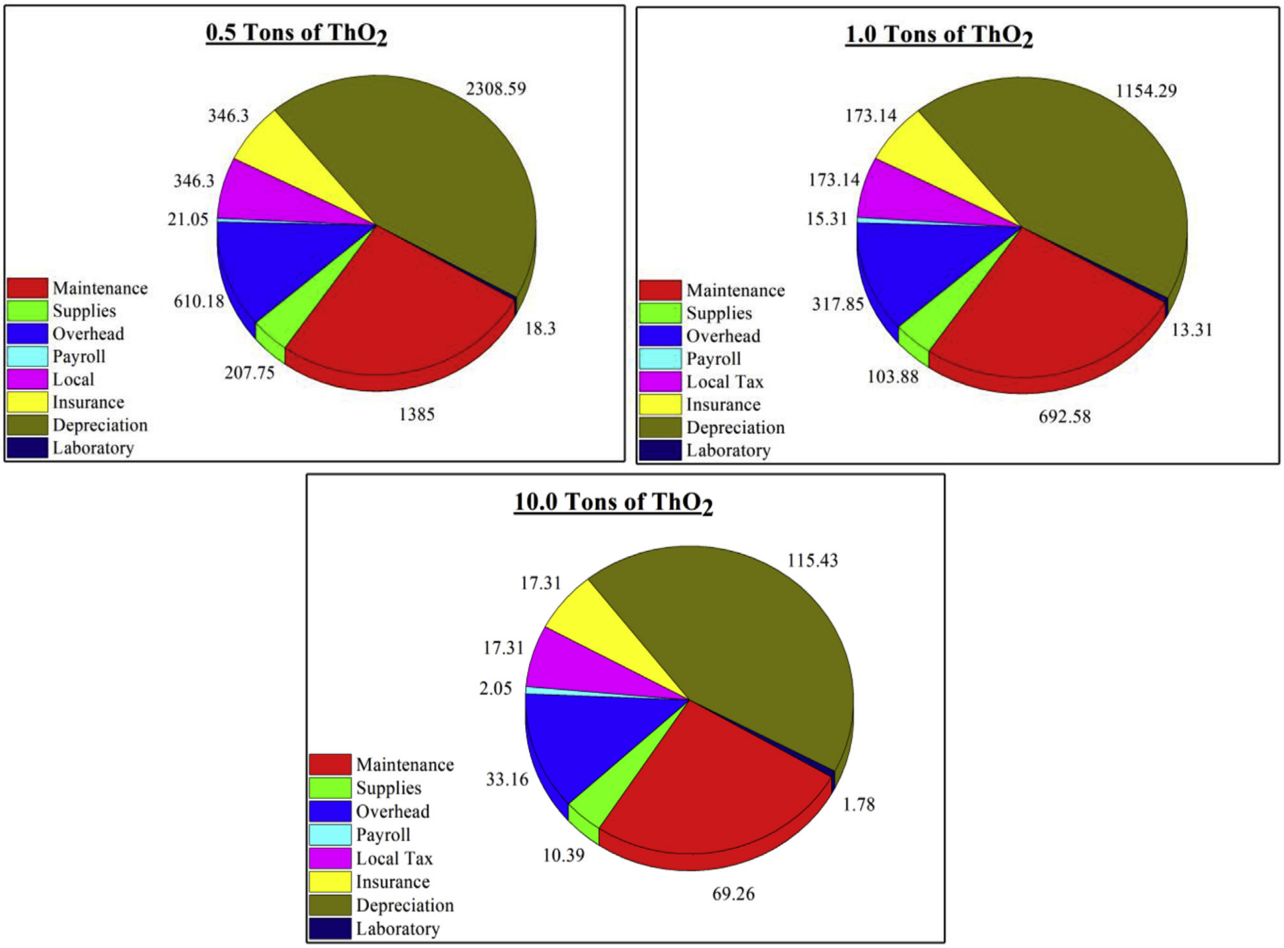

Fig. 3. Direct and indirect manufacturing cost distributions for 0.5, 1.0, and 10.0 tons of ThO_2, $/kg.

Table 4
Minimum and maximum cost of ThO_2 production for 0.5, 1.0, and 10.0 tons.

Mass Production, Tonnes	Total Cost \$/kg of ThO_2	
	Minimum	Maximum
0.5 tons	6829.79	6911.78
1 tons	3540.95	3592.94
10 tons	501.18	553.17

h are \$1865.28 kg^{-1}, \$1020.44 kg^{-1}, and \$207.23 kg^{-1} respectively. Meanwhile, the total indirect costs are \$1302.78 kg^{-1} (0.5 tons/h), \$664.13 kg^{-1} (1.0 tons/h) and \$67.78 kg^{-1} (10.0 tons/h). The results show that an increase in mass production will result in lower cost. Therefore, the operation at the plant scale needs to ensure higher production to reduce the cost of production.

3.3. *Determination of cost for 1 kg ThO_2*

Table 4 presents the minimum and maximum cost for the production of 1 kg of ThO_2 calculated based on 0.5, 1.0, and 10.0 tons/h ThO_2. The highest cost is at \$6829.79 – \$6911.78 kg^{-1} for 0.5 tons ThO_2. Meanwhile, the production cost of 1.0 ton shows an average value that ranges from \$3540.95 – \$3592.94 kg^{-1}. On the other hand, 10.0 tons records the lowest cost of production ranging from \$501.18 – \$553.17 kg^{-1}.

Therefore, it can be concluded that higher mass production contributes to lower production cost. Furthermore, the current production of ThO_2 is limited, and it is not commercially produced (USGS 2017). Previous studies recorded for thorium production were not discussed in detail, for example, Shaw [14] only discussed the leaching process which successfully estimated about \$9.11 – \$11.48 $pound^{-1}$ of thorium concentrates, Whatley [23] discussed the separation and purification process and estimated about \$2.07 $pound^{-1}$, and Barghusen [24] discussed oxalic precipitation and concluded that the estimated price was at a range of \$10.30 to \$13.12 per pound for the same production mass per month (5 tons).

4. Conclusion

An estimated cost and comparison for the production of 0.5, 1.0, and 10.0 tons of ThO_2 were investigated. The basis of this comparison was to determine the production cost of ThO_2 from monazite sand. The estimated costs for 0.5, 1.0, and 10.0 tons of ThO_2 production are \$6829.79 – \$6911.78 kg^{-1}, \$3540.95 – \$3592.94 kg^{-1}, and \$501.18 – \$553.17 kg^{-1} respectively. Based on the justified parameters, the cost of raw material for 0.5, 1.0, and 10.0 tons ThO_2 were determined to be \$63,126.00–\$104,120.77, \$126,252.00–\$178,241.53, and \$1,262,520.00–\$1,782,415.33 respectively. Furthermore, the total installed equipment cost was successfully estimated to be \$11, 542, 984.10. The total cost of \$ 13,274,431.715 was estimated for the entire mass production and the capital cost investment. The estimation and cost distribution indicated that higher mass production results in lower cost. In this study, the lowest cost recorded was \$501.18 – \$553.17 kg^{-1} for 10.0 tons of ThO_2 production.

Acknowledgement

This research was supported by Universiti Kebangsaan Malaysia, under the grant number GGPM-2017-084. The authors would like to acknowledge all lab technicians of the Nuclear Science Program, UKM for their technical support throughout the research.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2018.11.005.

Appendix A. Equipment cost for thorium extraction plant.

Equipment	Qty	Capacity/space/material for construction	Material comparison		F_{bm}	Actual cost bare module, C_{bm}
			2004	2018		
Reactor						
leaching vessel	1	Stainless steel vessel with average volume of 106.48 m^3	\$ 160,000.00	\$ 242,880.00	16.0	\$ 3 886 080.00
agitator	1	Agitator for leaching vessel, using power of 3.28 kW–36.06 kW	\$ 62,000.00	\$ 94 116	2.5	\$ 235 290.00
Total	2					\$ 4 121 370.00
Process vessels						
Solvent Extractor	1	3 stage mixer settler, with average settling area 102.22 m^2 and power 1.23 kW –24.64 kW	\$ 596,267.94	\$ 905,134.73	1.0	\$ 905,134.73
Stripper	1	5 stage mixer settler, with average settling area 255.55 m^2 and power 1.04 kW –20.83 kW	\$ 699,603.50	\$ 1,061,998.11	1.0	\$ 1,061,998.11
Total	2					\$ 1,295,254.86
Separators						
Vacuum filter for leacher	1	Belt filter, made to handle about average of 0.77 m^3/s with power 0.50 kW –4.63 kW	\$ 70,000.00	\$ 106,260.00	3.6	\$ 382 536.00
Precipitator	1	A stainless steel vessel, with average volume of 838.87 m^3	\$ 130,000.00	\$ 227,700.00	7.0	\$ 1 381 380.00
Precipitator agitator	1	Agitator for precipitator, uses 13.53 kW	\$ 15,000.00	\$ 22,770.00	2.5	\$ 21 360.00
Vacuum filter for Calciner	1	A Belt filter, use to hande about 0.001 m^3/s – 0.03 m^3/s	\$ 100,000.00	\$ 151,800.00	3.6	\$ 56 925.00
Total	4					\$ 1 842 201.00
Calciner						
Rotary Calcination Kiln	1	A Calciner with internal volume of 1300m^3, diameter = 3.0 m and a power of 195 kW	\$ 98,217.00	\$ 149,093.41	10.0	\$ 745 467.03
Total	1					\$ 745 467.03

(*continued*)

Equipment	Qty	Capacity/space/material for construction	Material comparison		F_{bm}	Actual cost bare module, C_{bm}
			2004	2018		
Pump						
Leacher concentrates Feed	1	Centrifugal pump with power 291 kW	$ 30,000.00	$ 45,540.00	5.2	$ 236 808.00
Leacher acid Feed	1	A 51.8 kW Pump	$ 18,000.00	$ 27,324.00	6.3	$ 172 141.20
Filtered leachate Feed	1	A 58 kW Pump	$ 18,500.00	$ 28,083.00	5.0	$ 140 415.00
Extraction Acid Feed	1	A 42 kW Pump	$ 16,000	$ 24,288.00	5.0	$ 121 440
Organic Feed	1	A 161 kW Pump	$ 27,000	$ 40,986.00	4.3	$ 176 239.80
Stripping Feed	1	A 130 kW Pump	$ 27,500	$ 41,745.00	4.3	$ 179 503.50
Oxalic Acid Feed	1	A 17 kW Pump	$ 10,000.00	$ 15,180.00	4.9	$ 74 382.00
Calciner Air Feed	1	A 331 kW Axial Fan	$ 1524.00	$ 2313.43	2.2	$ 5089.55
Total	8					$ 1 106 019.05
Total bare module cost		Actual material, C_{TBM}				$ 9,782,189.92
Contigency and fee		$C_c + C_F = C_{TBM} \times 0.18$				$ 1,760,794.19
Total module cost		C_{TM}				$ 11,542,984.11
Auxiliary (offsite) Facilities		C_{TBM} X 0.30				$ 2,934,656.98
Grass and Root capital		C_{GR}				$ 14,477,641.08

Appendix B. Composition of elements in monazite.

Element	Concentration in monazite leach solution (%)	Concentration, after extraction process (%) (By-product)
LREE		
La	34.36	14.73
Ce	37.49	28.81
Pr	0.81	5.30
Nd	3.12	3.88
Sm	0.49	4.39
Eu	0.04	2.71
Gd	0.42	4.01
HREE		
Tb	0.07	3.88
Dy	0.03	4.78
Ho	0.04	4.26
Er	0.19	1.68
Tm	0.01	3.75
Yb	0.09	3.62
Lu	0.01%	2.58
NORM		
Th	22.65	6.33
U	0.19	5.30

Appendix C. Cost of raw material and chemical reagent and it source.

Raw Material and reagent	Lab scale mass	$/tons (min)	$/tons (max)	sources
Malaysian Monazite	Ratio 1:10	$ 1680.00	$ 1900.00	Malaysian mineral resource industry
Sulfuric acid		$ 188.00	$ 240.00	ICIS Vendor Quote
Ammonium hydroxide	13.4 M	$ 200.00	$ 300.00	ICIS Vendor Quote
Nitric Acid	4 M	$ 200.00	$ 220.00	ICIS Vendor Quote
Tri-butyl phosphate	(30:70)	$ 1000.00	$ 1500.00	ICIS Vendor Quote
Kerosene		$ 200.00	$ 250.00	ICIS Vendor Quote
Oxalic Acid	2 M	$ 400.00	$ 700.00	ICIS Vendor Quote

Sources: Chemical Industry News & Chemical Market Intelligence (ICIS.com), Vendor identities are anonymous per vendor requests

Appendix D. The detail of equipment cost, size and power.

Equipment	Details
Reactor	
Leaching vessel	The proposed material for the leaching vessel was stainless steel 304 (SS304) that able to sustain at high temperature of 870 °C [25] Leaching vessel was used to digest monazite sand with sulfuric acid at 230 °C for 4 h to convert into Th sulfate. It is also important to note that the leaching vessel needed to operate at 40 barg due to the temperature being 230 °C [13]. Eq.14 and Eq. 15 were used to determine the volume and size of the leaching vessel. $V_{leach} = q \times R_{es}$ (14) $H = \frac{V_{leach}}{D}$ (15) where V_{leach}, q, and R_{es} are the volume of the vessel, flow rate of the chemical per hour, and time respectively, while H and D refer to the height and diameter of the vessel respectively. Cost for Leaching vessel: $C_{vessel} = \$\,160\,000 \times 16 \times \frac{607.2}{400} C_{vessel} = \$\,3\,886\,080$
Leaching vessel agitator	The agitator was used to dissolve the monazite sand. The power used in this process was calculated based on Eq.16: $P_{ag} = 0.4 \times (V_{leach})^{0.8}$ (16) where P_{ag} is power for the agitator. Cost for Vessel agitator: $C_{vessel} = \$\,62\,000 \times 2.5 \times \frac{607.2}{400} C_{vessel} = \$\,235\,290$
Process vessels	
Solvent extractor and stripper	The solvent extractor and stripper was used to purify thorium from other impurities. The equipment for this process includes a mixer and a settler. The costs for the solvent extractor and power usage were calculated using Eq. 17 and Eq. 18: $Volume = N_{stage} \times q_{total} \times R_{time}$ (17) $P_{tot} = \frac{0.03HP}{gal} \times \frac{264.17\ gal}{m^3} \times \frac{1\ kW}{1.34\ HP} \times V$ (18) Cost Extractor: $C_{extractor} = \$\,596\,267.94 \times 1.0 \times \frac{607.2}{400} C_{extractor} = \$\,905,134.73$ Cost Stripper: $C_{extractor} = \$\,699,603.50 \times 1.0 \times \frac{607.2}{400} C_{extractor} = \$\,1,061,998.11$
Separator	
Vacuum filter for leachate & vacuum filter for precipitate	Vacuum filter for leacher belt was used to separate the solid from the aqueous solution. Meanwhile, a precipitation filter was applied to remove thorium oxalate from the aqueous waste in the same fashion as the leachate filter. Eq. 19 was used to determine the size of the filter and Eq.20 was used to calculate power usage for the leacher filter. $A_{filter} = \frac{q}{0.01}$ (19) $P_{ag} = 0.4 \times (V)^{0.75}$ (20) Cost Calculation for leachate filter: $C_{leacherfilter} = \$\,70\,000 \times 3.6 \times \frac{607.2}{400} C_{leacherfilter} = \$\,382\,536$ Cost Precipitation filter: $C_{prep.filter} = \$\,100\,000 \times 3.6 \times \frac{607.2}{400} C_{prep.filter} = \$\,546\,480$
Precipitator & precipitator agitator	Precipitator is the equipment of removing thorium from the aqueous phase. This process was assumed to be done using an agitated process vessel. Eq.14 was used to determine the size of the vessel, and Eq. 16 was used to calculate the power usage. Cost for precipitator (vessel and agitator) $C_{pre.\ vessel} = \$\,130\,000 \times 7 \times \frac{607.2}{400} C_{pre.\ vessel} = \$\,1\,381\,380 C_{prep.\ ag} = \$\,15\,000 \times 2.5 \times \frac{607.2}{400} C_{prep.ag} = \$\,56\,925$
Calcination kiln	
Calciner	Calciner was used to convert insoluble thorium oxalate into thorium dioxide. The size and volume were calculated using Eq.21 and Eq.22. This was done using the mass flow rate relationship to diameter and length. Meanwhile, the power required was given using Eq. 23. $m = L \times D^2$ (21) $V_{internal} = L \times \pi \times \frac{D^2}{4} \times m$ (22) $P_{cal} = 0.15 \times V_{internal}$ (23) $V_{internal}$ and P_{cal} refer to volume and power used for calcination kiln respectively. Cost for Rotary Calcination kiln: $C_{kiln} = \$\,98\,217 \times 5 \times \frac{607.2}{400} C_{kiln} = \$\,745\,467.03$

Appendix E. Mass (kg) or volume (L) of raw material and chemicals consumption in thorium extraction process.

Material/Chemical	0.5 tons	1.0 tons	10.0 tons	Mass/kg
Monazite	12.5	25.0	250.0	16.7
H_2SO_4	25.0	50.0	500.0	33.3
NH_4OH	60.0	120.0	1200.0	80
Nitric acid	11.9	23.8	238.4	5
TBP/Kerosene	15.0	30.0	300.0	20
$C_2H_2O_4$	31.5	63.0	630.2	42.0

*1 kg = 1 L
Calculation method.

$$m_{n,1} = \frac{500kg}{0.0015kg} = 333,333.33$$

$$m_{n,2} = \frac{1000kg}{0.0015kg} = 666,666.67$$

$$m_{n,3} = \frac{1000kg}{0.0015kg} = 6,666,666.67$$

Appendix F. Processing thorium extraction process for 0.5, 1.0 and 10.0 tons production of ThO_2.

Chemical process	Molar mass (kg/mol)	Total Mass Consumptions to produce ThO_2 per month (kg/hr)		
		0.5 tons	1 tons	10 tons
Monazite	N/A	52.08	104.17	1041.67
H_2SO_4	98.08	104.17	208.33	2083.33
$Th(SO_4)_2$		520.83	1041.67	10416.67
NH_4OH	35.05	250.00	500.00	5000.00
$Th(OH)_4$	300.04	15.63	31.25	312.50
HNO_3	63.01	49.67	99.33	993.33
$Th(NO_3)_4$	480.04	208.33	416.67	4166.67
TBP	266.32	208.33	416.67	4166.67
$Th(NO_3)_4$ concentrates	480.04	416.67	833.33	8333.33
$C_2H_2O_4$	90.04	131.30	262.60	2626.04
$Th(C_2O_4)_2$	408.04	4.58	9.17	91.67
ThO_2	264.04	3.13	6.25	62.50

Appendix G. Manufacturing cost summary.

Capital			
Fixed Capital, C_{FC}			$ 11,542,984.11
Working Capital (15% of C_{FC})			$ 1,731,447.62
Total Capital Investment			$ 13,274,431.72
Direct Manufacturing cost			
	$/kg (0.5 tons)	**$/kg (1.0 tons)**	**$/kg (10 tons)**
Raw material, monazite	Refer Table 3		
Reagent			
Operating labor	122.01	88.73	11.87
Supervisory labor (15% of operating labor)	18.30	13.31	1.78

(continued on next page)

(*continued*)

Capital			
Utilities			
Steam (45 barg @ 0.0121/kg) 68,198.81 kg	1.65	0.83	0.08
Electricity ($ 0.053 kWh^{-1})	0.66	1.11	17.89
Process water ($ 0.016 m^{-3})	10.61	10.61	10.61
Maintenance (6% C_{FC})	1385.00	692.58	69.26
Supplies (15% Maintenance and repair)	207.75	103.88	10.39
Laboratory (15% of Operating labor)	18.30	13.31	1.78
Payroll charge (15% Labor & Supervision)	21.05	15.31	2.05
Total	**1865.28**	**1020.44**	**207.23**
Indirect Manufacturing cost:			
Overhead (40% Labor, Supervision, Maintenance)	610.18	317.85	33.16
Local taxes (1.5% of fixed capital)	346.30	173.14	17.31
Insurance (1.5% of fixed capital)	346.30	173.14	17.31
Total:	**1302.78**	**664.13**	**67.78**
Total manufacturing cost	**3168.07**	**1684.57**	**275.01**
General Expenses			
Administrative costs (25% of overhead)	152.54	79.46	8.29
Research and development (5% of Fixed capital)	1154.30	577.15	57.71
Total General Expenses	**1306.84**	**656.61**	**66.00**
Depreciation (10% of fixed capital)	2308.59	1154.29	115.43
Total Cost	**6703.54**	**3414.70**	**374.92**

*The total cost is not included the raw material and reagent cost as the total cost can be obtained in Table 4.

References

[1] W.M. AL-Areqi, A.A. Majid, S. Sarmani, C.N.A.A.Z. Bahri, Thorium: issues and prospects in Malaysia, AIP Conference Proceedings 1659 (2015), 040005-1 - 040005-6.

[2] P.E.O. Lainetti, Thorium and its future importance for nuclear energy generation, International Nuclear Atlantic Conference (2015) 1–6.

[3] A.F. Ismail, M.S. Yim, Investigation of Activated Carbon Adsorbent Electrode for Electrosorption-based Uranium Extraction from Seawater, vol. 47, 2015, pp. 579–587.

[4] J. Park, E.B. Farfán, C. Enriquez, Thermal transport in thorium dioxide, Nuclear Engineering and Technology (2018) 1–7, https://doi.org/10.1016/j.net.2018.02.002.

[5] Gen-IV International Forum, Very high temperature reactor (VHTR) [24 april 2018], https://www.gen-4.org/gif/jcms/c_42153/very-high-temperature-reactor-vhtr?id=c_42153 & portal=j_55&printView=true.

[6] W.M. Al-Areqi, C.N.A.C.Z. Bahri, A.A. Majid, S. Sarmani, Solvent extraction of thorium from rare earth elements, Malaysia Journal of Analytical Sciences 21 (2017) 1250–1256.

[7] C.N.A.C.Z. Bahri, W.M. Al-Areqi, A.A. Majid, M.I.F.M. Ruf, Penghasilan unsur nadir bumi daripada mineral monazit menggunakan pemendakan terpilih, Malaysian Journal of Analytical Sciences 20 (2016) 44–50.

[8] S.H. Joo, Y.U. Kim, J.G. Kang, H.S. Yoon, D.S. Kim, S.M. Shin, Recovery of molybdenum and rhenium using selective precipitation method from molybdenite roasting dust in alkali leaching solution, Mater. Trans. 53 (2012) 2038–2042.

[9] A. Kumari, R. Panda, M.K. Jha, J.R. Kumar, J.Y. Lee, Process development to recover rare earth metals from monazite mineral: a review, Miner. Eng. 79 (2015) 102–115.

[10] F. Sadri, F. Rashchi, A. Amini, A. Hydrometallurgical digestion and leaching of Iranian monazite concentrate containing rare earth elements Th, Ce, La and Nd, Int. J. Miner. Process. 159 (2017) 7–15.

[11] R.H. Perry, H. Cecil Chilton, Perry's Chemical Engineers' Handbook, eighth ed., McGraw-Hill, New York, 2008 (Chapter 9).

[12] C.N.A.C.Z. Bahri, A.F. Ismail, A.A. Majid, M.I.F.M. Ruff, W.M. AL-Areqi, Extraction and purification of thorium Oxide (ThO_2) from monazite mineral, Sains Malays. 47 (2018) 1873–1882.

[13] S. Archambault, Economic Analysis of Rare Earth Elements Extraction from Clay Waste, Thesis, University of Tennessee, 2017.

[14] K.G. Shaw, A Process for Separating Thorium Compound from Monazite Sand. Chemical Engineering Theses and Disertation, Iowa State University, 1953.

[15] W.M. Al-Areqi, C.N.A.C.Z. Bahri, A.B. Majid, S. Sarmani, Separation and radiological impact assessmant of thorium in malaysian monazite processing, Malaysian Journal of Analytical Sciences 20 (4) (2016) 770–776.

[16] Gael D. Ulrich, P.T. Vasudevan, Chemical Engineering Process Design and Economics: a Practical Guide, Process Publishing, Durham, 2004.

[17] L.S. John, G.W. Thomas, Cost Estimation: Concepts and Methodology, Health and Environmental Impacts Division, U.S. Environmental Protection Agency, 2017.

[18] The Academy of Science Malaysia, Rare Earth Industries: Moving Malaysia's Green Economy Forward, Perpustakaan Negara Malaysia, Kuala Lumpur, 2011.

[19] W.S. Garrett, Economic Analysis of Rare Earth Element Recovery from Clay, Theses. University of Tennessee, 2017.

[20] International Atomic Energy Agency, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, IAEA Safety standard, 2011.

[21] R.M. Sari, General process plant cost estimating (engineering design guideline), 21, KLM Technology Group, 2014.

[22] Payscale, Salary comparison, salary survey and search wage. www.payscale.com, october 2018.

[23] M.E. Whatley, Purification of Thorium by Solvent Extraction, Retrospective theses and dissertations, Iowa State University, 1953.

[24] J.J. Barghusen Jr., Processing of Monazite Sand. Retrospective Theses and Disertations, Iowa State University, 1957.

[25] Atlas Steels, Stainless Steel Grade Datasheets, Atlas Steels Technical Department, 2013.