EFFECT OF THORIUM FUEL ADDITION IN THE CONFIGURATION OF PUSPATI TRIGA REACTOR

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A Thesis Submitted to the College of Graduate Studies, Universiti Tenaga Nasional in Fulfilment of the Requirements for the Degree of

Master of Mechanical Engineering

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DECLARATION

I hereby declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously and is not concurrently submitted for any other degree at Universiti Tenaga Nasional or at any other institutions. This thesis may be made available within university library and may be photocopies and loaned to other libraries for the purpose of consultation.

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ABDUL HANNAN BIN DAMAHURI

Date:

ABSTRACT

A neutronic configuration analysis of thorium fuel has been conducted to PUSPATI TRIGA Reactor (RTP) that are using uranium zirconium hydride ($U\text{-}ZrH_{1.6}$) as fuel. Sixty nine core configurations have been simulated in this project, with each core has different investigated parameters. The project use the design of core RTP, which is core #1 as the reference. It has a similar dimension, criticality (484 PCM difference), and flux distribution with the original core of RTP. There are three main core variations, namely core-01, core-02, and core-03 that are modelled and simulated. Core-01 has additional numbers of thorium fuel rods. Core-02 has extra rods of thorium fuel in ring F with subtraction of uranium fuel rods in the core. Lastly, core-03 has an arrangement of thorium fuel rods in a seed-blanket unit. All three main configurations have ten variations with each of them has different numbers of fuel rods. These variations are labelled from 'A' until 'J'. This work also investigates other configurations such as the checker box design, ring by ring design, and diamond shape design. Other important variables are also studied, such as power, mass, and types of thorium fuels. All these configurations are simulated using MCNPX to determine its criticality, flux distribution, burnup rate, and uranium-233 buildup. Results show that core-Ct has the highest production of uranium-233 with 334.9 gram, and core-Bt has the longest lifecycle, which is 399 days. Thermal fluxes recorded from all simulated configurations are almost similar to the actual RTP core's flux, ranging from 4.28×10^{12} to 1.36×10^{13} n/cm^{2}s. Overall, the seed-blanket configuration offers the most favourable characteristics, especially criticality, that can be beneficial for PUSPATI TRIGA Reactor (RTP).

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LIST OF ABBREVIATIONS

MNA	-	Malaysia Nuclear Agency
PUSPATI	-	Pusat Penyelidikan Atom Tun Ismail
TRIGA	-	Training, Research, Isotope, General Atomics
NORM	-	Natural occurring radioactive material
REE	-	Rare earth element
MCNPX	-	Monte Carlo n-Particle eXtended
RTP	-	PUSPATI TRIGA Reactor
$U\text{-}ZrH_{1.6}$	-	uranium zirconium hydride
NAA	-	neutron activation analysis
SANs	-	Small Angles Neutron Scattering
NuR	-	Neutron Radiography
PGNAA	-	Prompt Gamma Neutron Activation Analysis
BNCT	-	Boron Neutron Capture Therapy
wt.%	-	weight percentage
B_4C	-	boron carbide
MeV	-	Mega electron volts
SCRAM	-	safety control rod axe man
EOC	-	end of cycle
BOC	-	beginning of cycle
β	-	fuel performance
MWd	-	megawatt day

LIST OF PUBLICATIONS

1. Damahuri, A. H., Mohamed, H., Mohamed, A. A. and Idris, F. (2018) ‘Utilization of thorium and U-ZrH1.6 fuels in various heterogeneous cores for TRIGA PUSPATI Reactor (RTP)’, *IOP Conference Series: Materials Science and Engineering*, vol. 298, p.012034.

2. Damahuri, A. H., Mohamed, H., Mohamed, A. A. and Idris, F. (2018) ‘An investigation into the feasibility of thorium fuels utilization in seed-blanket configurations for TRIGA PUSPATI Reactor (RTP)’, *IOP Conference Series: Materials Science and Engineering*, vol. 298, p.012035.

3. Damahuri, A. H., Mohamed, H., Mohamed, A. A., Rabir, M. H. and Idris, F. (2018) ‘Preliminary Analysis on Utilization of Thorium And U-Zrh$_{1.6}$ in PUSPATI TRIGA Reactor Core’, *Journal of Nuclear and Related Technologies*, Vol 15(2), p. 22-30.

4. Damahuri, A. H., Mohamed, H. and Mohamed, A. A. (2017) ‘Overview on Thorium in Research Reactors’, *Journal of Nuclear and Related Technologies*, vol. 14(2), p. 11-17.

CHAPTER 1

INTRODUCTION

1.1 Background Study

Thorium is a potential material for nuclear fuel. Through Malaysian Nuclear Agency (MNA), the Malaysian government is currently working on thorium extraction study. The agency, however, has given less attention to the actual utilization of thorium, especially for its potential use in Malaysia's Pusat Penyelidikan Atom Tun Ismail (PUSPATI) Reactor. The PUSPATI reactor is also known as the Training, Research, Isotope Production, and General Atomics (TRIGA) Reactor. Thorium as nuclear fuel can have several advantages, which include a higher abundance in nature compared to uranium, improved proliferation resistance, and lower waste radiotoxicity [1]. Therefore, this work proposes to utilize thorium-based fuels for the TRIGA reactor by strategically adding thorium fuels into the core. The project use Monte Carlo n-Particle eXtended (MCNPX) program to simulate the core configuration. The Monte Carlo method are proven to be the best method in order to determine the behavior of neutron. By using deterministic method, uses of MCNP varies from nuclear reactor design, radiation shielding and radiological health. The 3D geometrical model in MCNP help the simulation and interpretation process easily. In order to construct the 3D geometrical model, combination of analytical surfaces such as planes, cylinders and spheres need to be done. Then, the Boolean logic need to apply to get the desired shapes with exact position and parameter. Various study on materials composition and proportion variation analysis have been done. The variation analysis help to determine reactor core configurations that can achieve favorable core parameters such as long fuel burnup cycle, higher production of uranium-233, distribution of neutron flux and critical k_{eff} value. The outcomes of this work may benefit the nation and Malaysian Nuclear Agency, as this project provides a set of options to configure the TRIGA reactor core with thorium fuels and hence efficiently use thorium. Additionally, the results of the work can be used to provide a benchmark when designing the TRIGA reactor core with thorium fuels, which can be referred to by MNA researchers and TRIGA operators.

1.2 Problem Statement

Thorium is one of the natural rare earth elements that exists in Malaysia's rare earth extraction industry. The existence of thorium, however, has become a concerning issue to the public because of misinformation about the naturally occurring radioactive material (NORM), which is defined as industrial wastes or by-products enriched with radioactive elements. This project proposes to improve thorium utilization in the TRIGA reactor by first introducing thorium fuels into the core. Later, it investigates the effect of manipulating the composition of thorium fuel with uranium fuel ($U\text{-}ZrH_{1.6}$) inside the core, by modeling and analyzing several potential core designs. The designs include seed-blanket configuration, checker box configuration, alternate ring configuration and diamond shape configuration. For each configuration, important parameters, such as multiplication factor (criticality), fuel burnup cycle, uranium-233 buildup, and neutron flux distributions are analyzed and compared between the core designs.

Monte Carlo n Particle eXtended (MCNPX) is the best software to construct computational analysis because of the availability of burnup feature. Transmutation process and burnup have been included in MCNPX package. One of the features include Cinder90 depletion code that can be used to conduct burnup process. CINDER90 uses intrinsic cross section and decay data for 63 neutron energy groups to track the time-dependent reactions of 3400 isotopes [3]. CINDER90 contains all its data in a single file, cinder.dat, which is packaged in the MCNPX 2.6.0 data folders. Inside cinder.dat, all 3400 isotopes are listed with their 63-group reaction cross section information. Isotope identifying-numbers contain an atomic mass number, an atomic number, and a digit designating a ground or metastable state [4].

1.3 Objectives of the Study

1. To perform core computational analysis simulation using MCNPX code on PUSPATI TRIGA Reactor.

2. To investigate the neutron multiplication factor, flux distribution, uranium-233 buildup and fuel cycle length of different types of core configurations with the addition of thorium fuels.

3. To identify the configurations with the addition of thorium that would be suitable for PUSPATI TRIGA Reactor (RTP) operation.

1.4 Research Scope

The study focuses on one type of nuclear reactor, which is the PUSPATI TRIGA Reactor. The reactor has been operated since 1987 as it is the only research reactor in Malaysia. The reactor uses uranium zirconium hydride (U-$ZrH_{1.6}$) with 19% of enrichment of uranium-235 with three different weight percentages, namely 8.5, 12 and 20 wt.%.

Thorium oxide is introduced to the core of PUSPATI TRIGA Reactor to study the neutronic behavior of the core. Thorium is a fertile element which cannot merely undergo fission process with thermal neutrons. Hence, there might be a different neutronic performance compared to that of uranium fuels (U-$ZrH_{1.6}$). The neutronic performance of thorium is analyzed using Monte Carlo n Particle eXtended (MCNPX) code that predicts the behavior of neutron properties. Essential parameters such as criticality, burnup fuel cycle, total flux distribution, and power peaking factor are observed and evaluated.

1.5 Layout of Thesis

The thesis is organized into five chapters which are:-

Chapter 1 that introduce the purpose of simulation of MCNPX with its advantages, objectives and the scope of study.

Chapter 2 gives the basic information about neutronic study and Monte Carlo simulation method.

Chapter 3 shows the details of methods, including the number of configurations, different type of configuration and parameter such different mass, reactor power and type of thorium fuel.

Chapter 4 explains the result from MCNPX simulation. The results are discussed based on multiplication factor, neutron flux, lifecycle of the core and uranium-233 buildup.

Chapter 5 concludes and summarize the best core configuration for the study and recommendation for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Malaysia Nuclear Agency

The PUSPATI TRIGA Reactor (RTP) is the only research reactor in Malaysia, which has been operated for almost 35 years. The reactor achieved its criticality on 28 June 1982 [11-15]. The reactor was constructed to fulfill various nuclear applications such as for research, education, and irradiation services for companies. Several facilities are available in the reactor such as neutron activation analysis (NAA), small angles neutron scattering (SANs) and neutron radiography (NuR). Besides, there is also a prompt gamma neutron activation analysis (PGNAA) and boron neutron capture therapy (BNCT). Figure 2.1 shows the cross section of RTP from a side view.

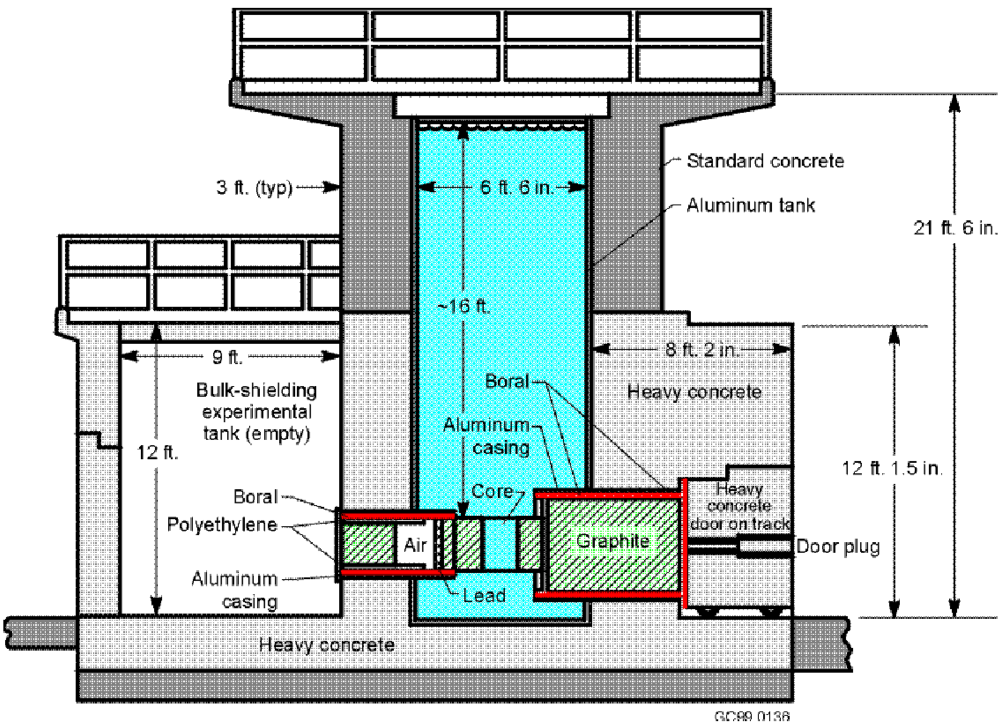


Figure 2.1: Cross section of PUSPATI TRIGA Reactor (RTP) [16]

2.2 PUSPATI TRIGA Reactor (RTP)

The PUSPATI TRIGA reactor (RTP) is a TRIGA Mark II Pool-Type Reactor with its maximum power of 1 MW thermal. The reactor uses Uranium Zirconium Hydride ($U\text{-}ZrH_{1.6}$) with three different types of weight percentage, namely 8.5 wt.%, 12 wt.% and 20 wt.% with the enrichment of 20% [11-18]. The reflector of the reactor is made of graphite, which acts to reflect neutrons in the reactor to prevent them from escaping the core. The thermal flux of RTP at central thimble is 8.7×10^{12} n/cm^{2}s [13]. The control rod material is boron carbide, and there are four types of control rods with three of them fuel follower type and one air follower type. Fuel follower control rod made up with 8.5 wt.% $U\text{-}ZrH_{1.6}$ and B_4C absorber on top of fuel section while air follower control rod contains air section with B_4C absorber on top of the fuel [11-14]. Control rods are used to control the reactor. The movement of control rods (up and down) affects the multiplication factor of the core [5]. When the control rods pull upward, the multiplication factor will be increased and vice versa. The reactivity of a nuclear reactor depends on the insertion of control rods. Control rods are made from boron have strong thermal neutron absorption cross-section that prevent chain reaction occur in the core as the neutron produce are absorbed from boron. The coolant for the reactor is light water that has undergone a demineralizing process. Figure 2.2 shows the arrangement of fuel in the core of RTP. The cylindrical fuels are arranged in multiple circular rings that have water filled between each fuel [11, 12, 14].

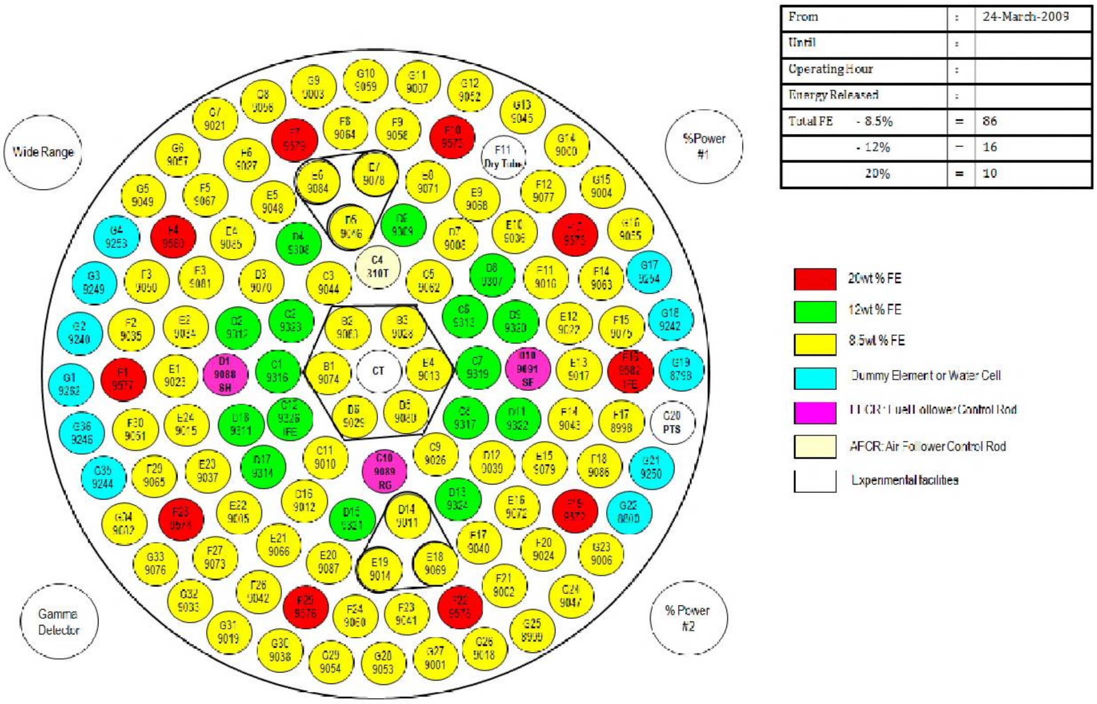


Figure 2.2: PUSPATI TRIGA Reactor (RTP) core-14 configuration [19]

As for the operation, RTP operates for four to six hours per day and four days per week, as shown in Figure 2.3 below. The operational hour of the reactor depends on the demand from users who are using the irradiation facility of the reactor.

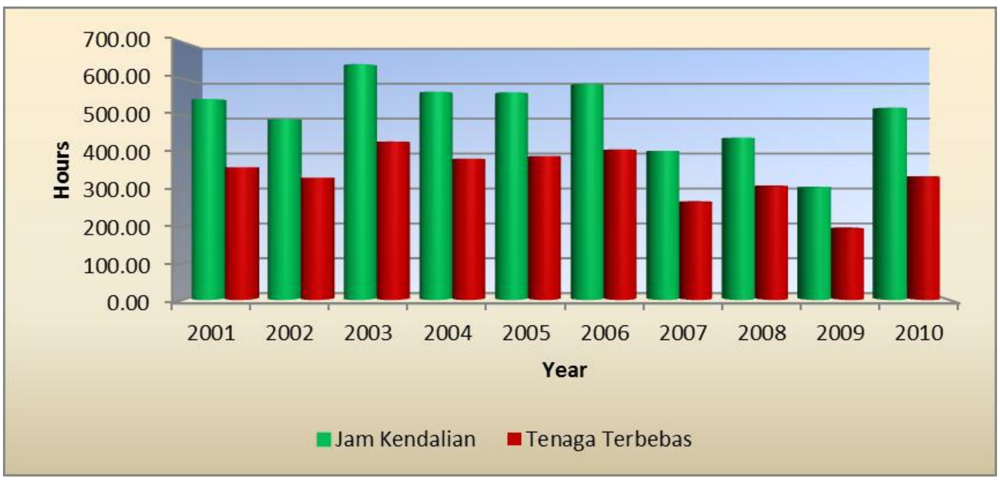


Figure 2.3: RTP operating hours for the past ten years [20]

2.3 RTP Fuel

PUSPATI TRIGA Reactor uses a homogenous type mixture of hydride fuel which is U-$ZrH_{1.6}$ for the fuel [14]. The fuel is a standard TRIGA cylindrical rod from General Atomic that has an outer diameter of 3.63 cm and a height of 38.1 cm. At the centre of the fuel, a zirconium rod is fitted in with a radius of 0.3175 cm. The fuel is protected by a stainless steel (SS-304) cladding with two cylindrical graphite end caps that have a height of 6.5 cm and 9.45 cm, respectively. The end caps are placed at the top and bottom of each fuel. Table 2.1 and Figure 2.4 show the details of the RTP fuel.

Table 2.1: Specification of TRIGA fuel [11, 14, 15]

	Fuel Element	Control rod
Geometry		
Outer radius of Zr rod (cm)	0.3175	0.3175
Outer radius of fuel (cm)	1.765	1.665
Air gap thickness (cm)	0.05	0.05
Cladding thickness (cm)	0.05	0.05
Fuel composition		
Uranium (wt.%)	8.5, 12, 20	8.5
Enrichment (wt.%)	19.7	19.7
H:Zr ratio	1.6	1.6
Absorber	-	B_4C

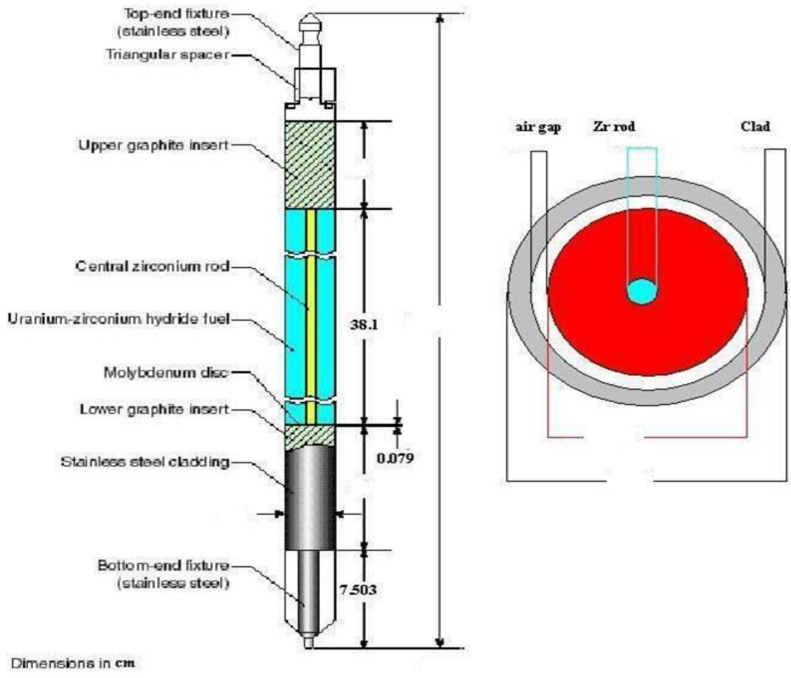


Figure 2.4: Fuel rod of RTP fuel [16]

The enrichment of the fuel is 19.7% with weight enrichment (wt.%) of 8.5, 12, and 20. The original number of fuel elements in the first criticality of RTP is 86. The fuels at the time consist of 8.5 wt.% U-$ZrH_{1.6}$. Each fuel contains a different weight of uranium-235 and uranium-238. Table 2.2 shows the content for each weight percentage for each fuel.

Table 2.2: Content in different wt.% of fuel [17]

Wt.%	Uranium-235	Uranium-238	Zirconium	Hydrogen
8.5%	38g	154g	2219.9g	38.9g
12%	54g	219g	2235.8g	39.2g
20%	97g	394g	2412.7g	42.3g

After several years of operation, fuel elements with 12 wt.% and 20 wt.% of U-$ZrH_{1.6}$ were gradually added to the core to maintain criticality of the reactor. At the moment, there is still no spent fuel produced from RTP although it has run for almost four decades.

2.4 Fission Chain Reaction

There are 4 factors that contribute the neutron life cycle in a thermal reactor such as fast fission factor, ε, resonance escape probability, p, thermal utilization factor, f, and thermal fission factor, η. Besides, there are two additional factor that required to calculate neutron life cycle which are thermal non-leakage probability, P_f and fast non-leakage probability, P_t [6]. Together all 6 factors are used to calculate neutron life cycle called effective multiplication factor. The effective multiplication factor can be denoted as equation 2.1 below

$$k_{\mathrm{eff}} = k_{\infty}.\mathrm{P_f}.\mathrm{P_t} \tag{2.1}$$

As for the infinite medium, there are no neutron leakage across the core and consist only 4 factors and denote as shown in equation 2.2 below

$$k_{\infty} = \eta.\varepsilon.p.f \tag{2.2}$$

The self-sustaining energy reaction from a nuclear fission reaction is called a chain reaction that caused from fission of fissile material. From the reaction, energy in the form of heat is produced along with the nuclear fission products and neutrons with a mean energy of 2 MeV. It is estimated that the produced energy for each reaction is around 200 MeV. The chain reaction can also be described in terms of a multiplication factor that is denoted by symbol *k*. The neutron multiplication factor is defined as a ratio of the number of neutrons at the end of a generation divides by the number of neutrons at the previous generation.

$$k_{\mathrm{eff}} = \frac{\text{number of neutrons in one generation}}{\text{number of neutrons in the previous generation}} \tag{2.3}$$

The value of *k* represents the state of the reactor. By referring to equation 2.3, if the value of *k* is greater than 1, it shows that the core is in a supercritical state, which is the energy release by chain reaction increases over time. On the other hand, the number of neutrons released is decreasing over time when it is in a subcritical state, or the value of k is lower than 1

The power of a reactor can be controlled by changing the value of k. A reactor operator may change the value of k to supercritical in order to increase the power of a reactor. For the RTP reactor, it can achieve the desired power by varying the position of control rods. When the reactor has achieved a targeted power level, the position of control rods remains in their final position. The power of the reactor can be shut down by dropping all the control rods to the core — this process is called, SCRAM, or famously known as the 'safety control rod axe man procedure' [21]. The value k_{eff} can be estimated in the MCNPX code, using a KCODE card. Figure 2.5 shows the KCODE card code used in the simulation.

```
KCODE 10000 1.00 50 150
```

Figure 2.5: KCODE card code

In order to get the significant value of k_{eff}, the reactivity difference formula is used to get the value as shown in equation 2.2 below. Where k_1 represent the experimental k_{eff} and k_2 is the actual value k_{eff} of RTP core [1, 39]. Percent mille (PCM) is the unit for reactivity that is one-thousandth of a percent %k/k. The unit is used because the reactivity change of a reactor is too small and unit of PCM allow the value to be written in whole number [9].

$$\Delta\rho = \frac{|k_1 - k_2|}{k_1 \times k_2} \times 10^5 \text{ pcm} \tag{2.4}$$

2.5 Fuel Burnup

Fuel burnup is the process to measure how much uranium is burn in the reactor. The higher the concentration of uranium in the fuel, the longer the fuel can sustain chain reaction and the longer lifetime of the fuel. It is measured in megawatt days (MWd). Specific burnup of the fuel, on the other hand, is defined by the fission released per unit mass of the fuel. The unit is written in megawatt days per metric ton or per kilogram (MWd/t) or (MWd/kg) [21].

Fractional burnup, which is also called fuel performance, β, is defined by the ratio of the number fission in a specific mass of fuel to the total number of heavy atoms in the fuel.

$$\beta = \frac{\text{number of fissions}}{\text{initial number of heavy atoms}} \tag{2.5}$$

Since fission of all fuel (β=1) yield 950 000 MWd/t, for ^{235}U,

$$\text{Specific burnup} = 950\ 000\beta\text{MWd/t} \tag{2.6}$$

```
burn time = 100 100 100 $ days

power = 1 $ MW

pfrac=1 1 1

mat= 1, 10

matvol= 32855.44, 7640.889446
```

Figure 2.6: Burnup card code

Figure 2.6 shows the example of burnup card used in the simulation. Burn time indicates the duration of fuel depletion, which is presented with a unit of days. Symbol $ represent the comment for the row, any character after $ symbol will be neglected. The next row is the power that represents total fission of the system in the unit of MW, and pfrac, which is the total fraction power applied to the burn time. As for mat and matvol, they are defined as a material number to be burned, as written in a material card of the MCNPX code, and the volume of all cell containing the material, respectively.

2.6 Neutron Flux

Neutron flux is define as neutron density multiply by neutron velocity that can be denoted as neutron/cm^2/sec [21]. There are two type of neutron fluxes constantly used which are thermal neutron flux and fast neutron flux. Each of the flux has different level of energy. Thermal neutron has 0.025 electron volt (eV) of energy while fast neutron is 1-20 MeV [9]. It is an important parameter for the neutronic analysis of a reactor as it affects the reaction rate and the fuel burnup. MCNPX code's tally card can be used to determine the value of neutron flux in a certain area. Figure 2.7 shows an example of tally card use in a simulation.

```
F2:N (surface number)................
F4:N (cell number)...............
```

Figure 2.7: Neutron flux card code

There are two types of tally that can be used to determine the flux in a simulation which is F2 and F4. F2 is the code to determine flux in specific surface geometry while f4 is the code for cell geometry. The unit for each tally type is derived from the unit of the source, such as particle/cm^2. The value from the MCNPX result needs to have a normalization process to get the real neutron flux value. Equations below show the formula to convert the value of MCNPX flux to neutron/cm^{2}s where n represent for number of neutrons, s is for second in time and v is for number of neutron produce for a fission.

$$\text{Actual flux}, \phi = \frac{\text{MCNP flux} \times \text{neutron total}}{k_{\text{eff}}} \tag{2.7}$$

$$\text{Total neutron}\left(\frac{\text{n}}{\text{s}}\right) = \frac{\text{Power (W)} * \text{v}(\frac{\text{n}}{\text{fission}})}{200\,\frac{\text{MeV}}{\text{fission}} * 1.6022\text{e}^{-13}(\frac{\text{J}}{\text{MeV}})} \tag{2.8}$$

The estimated maximum thermal flux at energy level below the power of 0.21 eV is 8.0×10^{13} n/cm^2/s. Whereas, the maximum fast flux at above the power of 10 keV is estimated to be 9.6×10^{13} n/cm^2/s [38].

2.7 Heterogeneous core

Most of the conventional reactors in the world use a heterogeneous core for the fuel arrangement. A heterogeneous reactor has a large number of fuel rods, which are surrounded by coolant. In a homogeneous reactor, the fuels and moderator are uniformly mixed. The homogenous type is rare to be practically configured because of the difficulties in component maintenance and erosion and corrosion. Figure 2.9 shows two examples of PWR heterogeneous cores. The core of the reactor can be in homogenous and heterogeneous structures. A heterogeneous fuel is a fuel that is not mixed with other material, while a homogenous fuel is the mixture of fissile materials with thorium. The fuel type arguably offers better neutronic characteristics compared with homogenous fuel [26]. One of the reasons is that the fuel is not mixed with thorium, and hence all the fuels can be arranged in a seed blanket configuration. The seeds could be enriched uranium, plutonium or recycled uranium-233. Although a heterogeneous fuel often gives better neutronic performance due to higher discharge burnup, the more power distribution and uneven burnup in the fuel assemblies can lead to drawbacks on the thermal-hydraulic side. On the other side, a homogenous fuel offers better thermal-hydraulic properties, but it needs to reach a discharge burnup of 120 GWd/tHM to be comparable to a homogenous uranium fuel [27].

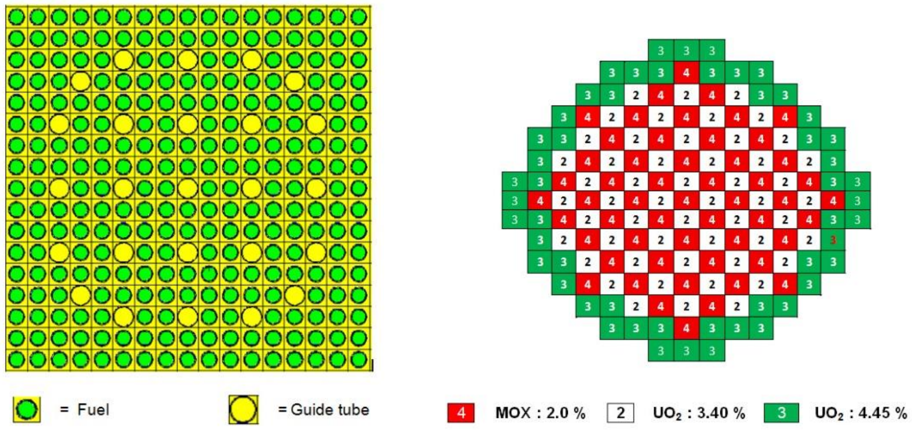


Figure 2.8: Heterogeneous core PWR [22]

2.8 Thorium History

In the 1950s, USA, Russia, and European countries started research work on thorium. By early 1960s, two nuclear power plants, namely Elk River Station and Indian Point Nuclear Power Plant, used a combination of high enriched uranium with thorium oxide as fuel. Until the late 1970s, Shippingport reactor, which was initially a uranium fuel reactor, produced breeding fuel by experimenting seed-blanket design using uranium-233 as its seed and thorium for the blankets with the breeding ratio of 1.01 [23]. The Shippingport Reactor was considered as the first commercial reactor and breeding reactor that have three different fuel cores [24, 25]. Different type of reactors such as high-temperature gas-cooled reactors (Peach Bottom 1 and Fort St Vrain) that use prismatic and pebble bed fuels has also been tested with thorium fuel and mostly built and tested in the USA, Germany and United Kingdom.

2.9 Thorium Properties

Thorium can occur naturally in rare earth element ores. Most thorium in the world can be found in Australia. The county contributes almost 18.7% of thorium production in the world. It is estimated that thorium is three to four times more abundant than uranium. The thorium half-life is three-times than that of ^{238}U (1.4×10^{10} years) [28]. The thorium fuel does not produce uranium-238 that can become Plutonium-239, which later can be misused for nuclear weapons. The productions of actinides from thorium fuel are lower compared with uranium fuel. Since thorium is lighter than uranium, it is considered less harmful because the production of actinides such as americium and curium are low than uranium fuel. Table 2.3 below show properties of thorium element.

Table 2.3: Specification of thorium

Properties	**Specifications**
Atomic Number	90
Electronegativity according to Pauling	$232.04 g.mol^{-1}$
Density	$11.72 g.cm^3$ at $20^{\circ}C$
Melting point	1750°C
Boiling point	4790°C
Van der Waals radius	0.182nm
Ionic radius	0.110nm
Isotopes	9
Electronic shell	$[Rn\}6d^2 7s^2$
Energy of first ionization	$1107.6 kj.\ mol^{-1}$
Energy of second ionization	$1962.4 kj.\ mol^{-1}$
Energy if third ionization	$2774 kj.\ Mol^{-1}$
Discovered by	John Berzelius

2.10 Fission Process of Thorium

Thorium is an element that cannot undergo fission process because it is a fertile material, and it needs neutron bombardment to convert it to a fissile material [29]. When the thorium is bombarded with neutrons, the thorium-232 absorbs a neutron and becomes thorium-233 and release gamma ray, γ as shown in equation 2.9

$$^{232}_{90}\mathrm{Th} + \mathrm{n} \rightarrow {}^{233}_{90}\mathrm{Th} + \gamma \tag{2.9}$$

Next, the thorium-233 undergoes a decay process to becomes protactinium-233 and release electron and neutrino, v as shown in equation 2.10

$$^{233}_{90}\mathrm{Th} \rightarrow {}^{233}_{91}\mathrm{Pa} + e^{-} + v \qquad (2.10)$$

Later, protactinium decays and becomes uranium-233, which then the uranium undergoes a fission process and release electron plus neutrino, v as shown in equation 2.11.

$$^{233}_{91}\mathrm{Pa} \rightarrow {}^{233}_{92}\mathrm{U} + e^{-} + v \qquad (2.11)$$

From the fission process, energy and neutrons are being released, while uranium-233 becomes thorium-232 again. All the steps above repeat for another thorium fuel cycle. Figure 2.10 shows the thorium cycle in a reactor.

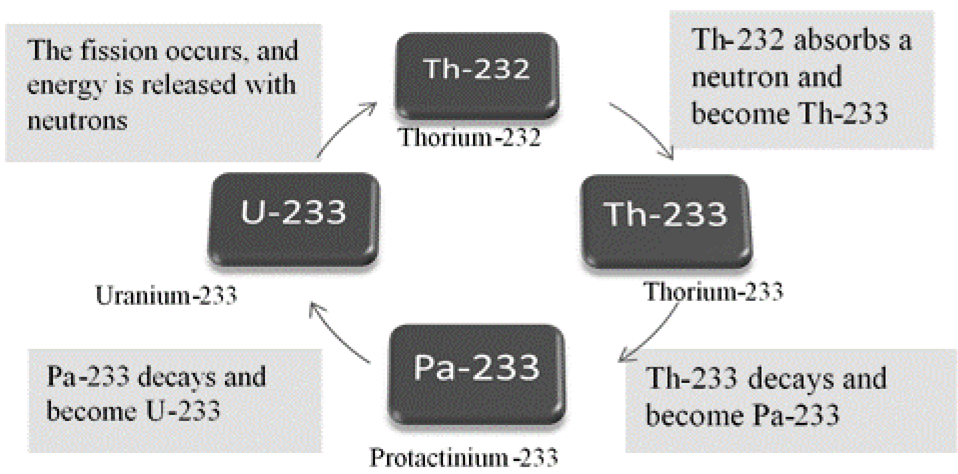


Figure 2.9: Thorium fuel cycle

2.11 Seed-blanket Configuration

The seed-blanket configuration is one of nuclear power plant core designs that consists of seed and blanket regions. The seed region is the region located at the center of the core that provides neutrons for the blanket region. Usually, the element in the seed region consists of a fissile element, such as uranium, which has 20% uranium-235 and 80% uranium-238 from the total uranium. The multiplication factor at the seed region in a seed-blanket core is typically higher than 1.

The enriched uranium is preferred in the form of rods or plates consisting of a uranium-zirconium alloy (uranium-zircalloy) or cermet fuel (uranium oxide particles embedded in a zirconium alloy matrix). For the blanket region, the element in the region is a fertile element which is thorium. Enriched uranium is added in a small amount to activate the blanket region at the early stage of reactor operation. The blanket region then absorbs neutrons provided from the seed region. In return, the thorium-232 in the blanket region changes to uranium-233, which later causes more fission to occur in the blanket region. The startup uranium is also added to the blanket region to denature residual of remaining uranium-233 at the end of its lifetime. The residual of uranium-233 is mixed with non-fissionable elements of uranium such as uranium-234, uranium-236, and uranium-238. This is done to prevent the proliferation of nuclear waste.

To control the reactivity of a reactor, light water is used as a moderator inside the seed-blanket core. There is, however, no boron is added into the water because it may decrease the multiplication factor of the blanket region. Boron will absorb neutrons from the seed region while neutrons are needed in the region. Figure 2.11 shows the seed-blanket unit configuration; the outer square represents the thorium blanket, and the inner square represents the uranium seed.

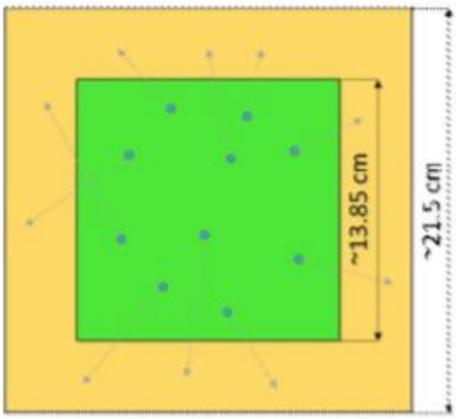


Figure 2.10: Seed-Blanket Unit [30]

2.12 Radkowski Thorium Reactor

Under the Bettis Atomic Power Laboratory's Light Water Breeder Reactor (LWBR) program, Radkowski has first proposed the seed-blanket concept. This concept is one of the most highly known thorium seed-blanket designs. Radkowski Thorium Reactor (RTR) has a similar pressurized water reactor (PWR) core design [31]. The element that is situated in the seed region is usually metal or oxide element. As for RTR, the seed element is UO_2. For the blanket, the element is ThO_2. The design focuses on the heterogeneous configuration of seed-blanket unit (SBU) fuel assembly. The blanket part is separated with the seed part to allow fuel independent with the seed while the seed part is supplying neutrons for the blanket.

The SBU fuel assembly can be compatible with the existing reactor such as PWR or VVER. With the heterogeneous seed-blanket design, it offers flexibility in fuel shuffling during refueling outages. The blanket of SBU is slightly added with UO_2 to generate power in the blanket and to produce uranium-233 in the blanket. The lifecycle of the blanket part is quite long, which is about ten years with a burnup of -100 MWd/kg. For the seed part, the element has to be replaced yearly.

Seed fuel is treated similar to standard PWR assemblies, with -1/3 of seeds replaced annually by fresh seeds; the remaining 2/3rds (partially depleted) of entire assemblies are reshuffled. Each fresh seed is loaded into an empty blanket, forming a new fuel type. These new fuel assemblies are reshuffled together with partially depleted blanket-seed assemblies to form a reload configuration for the next cycle.

2.13 Benefits of seed blanket unit

According to Bays in his ‘Report on Potential Advantages and Uncertainties of the Thorium Seed Blanket Unit Fuel Concept,' it is shown that the total percentage of actinide in a seed blanket unit is 16.7%, lower than that of the conventional VVER-1000 reactor [32]. Besides, it is estimated that the thorium blanket may produce less transuranic isotopes. Figure 2.12 shows the number of radiotoxicity decay of the

Radkowski PWR seed blanket unit in comparison to the PWR UOX. The number of radiotoxicity in the seed-blanket unit after discharge is lower than the radiotoxicity of PWR UOX reactor.

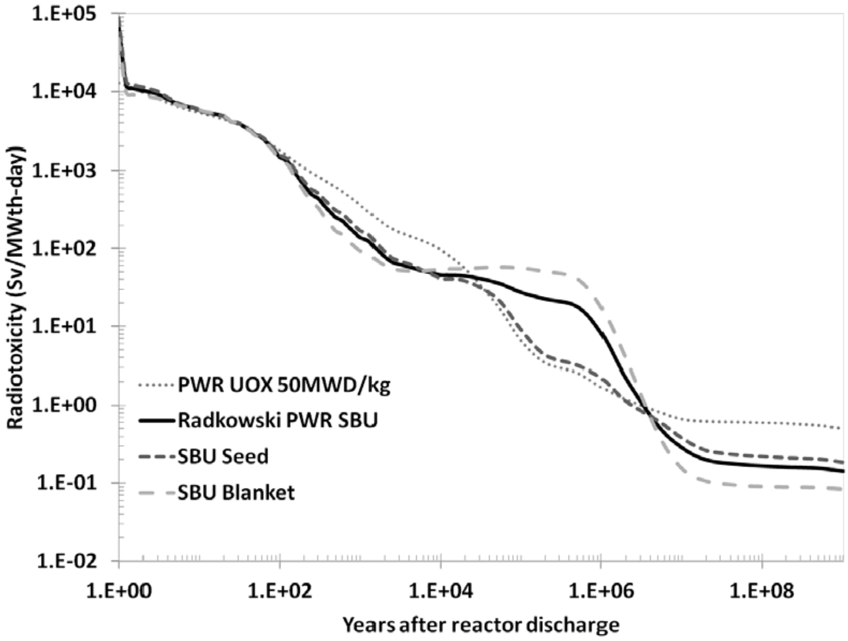


Figure 2.11: Radiotoxicity versus decay time, based on SBU concept [33]

2.14 Monte Carlo Simulations of Nuclear Fuel Burnup

It is very important for a nuclear reactor for having the simulation before starting the process. According to (Jervis, 1984), models and simulation have been used extensively and they provide a strong integrating influence on the total systems design [40]. As for RTP, various simulations have been done before the reactor started to commission. One of the most used simulator in RTP is Monte Carlo n-Particle simulator. Monte Carlo method has been used to determine the characteristic of parameter such as criticality. Using the KCODE command, MCNP approximates k_{eff} by estimating the number of fission neutrons produced per fission neutron started for a given generation. By repeating this process for thousands of generations MCNP arrives at a good approximation of a multiplication factor [14].

CHAPTER 3

METHODOLOGY

3.1 Introduction

The simulation work is based on the core PUSPATI TRIGA Reactor (RTP) of the Malaysia Nuclear Agency. The core consists of different types of weight percentage of uranium-235, which is analyzed with the presence of thorium fuel in the TRIGA reactor. Monte Carlo N-Particle Transport Code eXtended (MCNPX) is the main software used in the project to simulate the neutronic behavior of a reactor core. Monte Carlo method has gained more interest in neutronic computation because of its capability in accurately modeling 3D geometries [34]. MCNPX code uses probabilistic method (Monte-Carlo) to perform lattice physics calculations to estimate the criticality, neutron flux distribution and burnup rate of a fuel assembly in a full core [35]. The software is used for validation and verification purposes where the simulation results will be compared with the real values from the reactor core and other computational studies performed for the TRIGA reactor. This project is mostly computational, and it uses a high-performance computer when running the MCNPX code. Since MCNPX code uses a probabilistic approach, the calculation can be very computationally expensive. Figure 3.1 shows the flowchart for this project.

Firstly, the reactor core is designed and modeled using similar geometrical dimensions and materials of the real RTP core, including the fuel and moderator. Next, the data card which contains the material compositions of fuel and moderator is inserted to the code. Then, the MCNPX simulation is carried out to get the initial criticality, k of the core. The result of the initial criticality is validated and verified with the experimental result of RTP and previous simulation studies. Once the comparison result is deemed acceptable, the work continues by adding thorium fuel to the core. The configuration of the core is changed along with the arrangement of the fuel position and quantity of added thorium fuel rods. There are four actual RTP configurations with thorium fuel, namely core-01, core-02, core-03, and core-04 that have been studied. Each configuration consists of 10 sub-configurations that have different numbers of thorium fuels. The entire configuration is simulated to find the parameters needed.

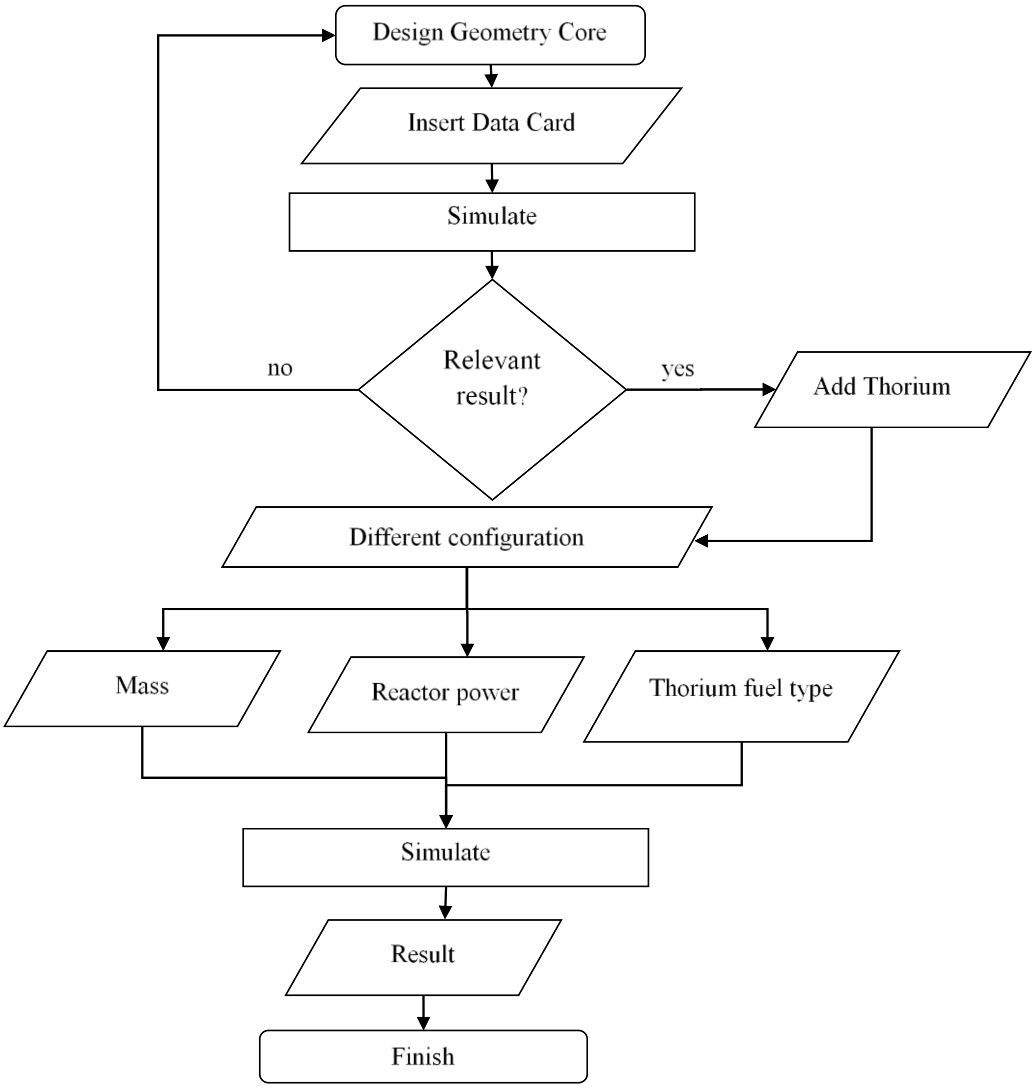


Figure 3.1: Methodology flowchart

3.2 Design of Basic Reactor Core

First, the reactor is designed using Monte Carlo N-Particle eXtended (MCNPX), which is the extended version of MCNP5 that can simulate the interaction of particles with 34 different types of particles. The data card used in MCNPX is ENDF data libraries. The initial criticality, *k*, calculation was carried out using KCODE with 10000 neutron population. Criticality, *k*, is defined as the ratio of the neutron production to neutron loss in a reactor. In a supercritical condition, the number of neutrons produced by fission reaction in one generation is higher than the number of neutrons in the previous generation due to the loss of neutrons. Hence, the *k* is larger than 1.0 for a supercritical condition. When the criticality, *k*, is under 1.0, it is considered as a subcritical condition. Most supercritical cores are designed for fast breeding reactors because the reactor needs neutrons to sustain its system and to breed other fissile material to sustain the cycle.

In the infinite medium of reactor core, k_∞ there are no neutron leakage across the core and consist only 4 factors that contribute the neutron life cycle in a thermal reactor such as fast fission factor, ε, resonance escape probability, p, thermal utilization factor, f, and thermal fission factor, η [6]. All 4 factor. Equation 3.1 below shows the formula for infinite medium for multiplication factor.

$$k_\infty = \eta.\varepsilon.\mathrm{p.f} \tag{3.1}$$

Besides, there are two additional factor that required to calculate neutron life cycle which are thermal non-leakage probability, P_f and fast non-leakage probability, P_t. Together all 6 factors are used to calculate neutron life cycle called effective multiplication factor. The effective multiplication factor can be denote as

$$k_{\mathrm{eff}} = k_\infty.\mathrm{P_f}.\mathrm{P_t} \tag{3.2}$$

The core designed is labelled with core #1 in order to not being mistaken with the original core 1 of RTP.For validation, the initial criticality obtained from MCNPX is with the real value measured directly from the PUSPATI TRIGA Reactor RTP, which is 1.05261 and from the experimental result, which is 1.05677 [14]. The accepted standard deviations for the results are less than 0.05 (5%) for a point detector and 0.1(10%) for other estimators such as power and flux calculation in reactor core [36]. The core is designed and simulated using MCNPX, and the fuel arrangement follows Core 1 of RTP. This core consists of 86 rods of uranium zirconium hydride ($U\text{-}ZrH_{1.6}$) with a weight percentage of 8.5% w.t. for each rod. The core is simulated to identify critical parameters that are relevant for analyzing the neutronic performance of the core. The parameters are criticality, burnup percentage of the fuels, neutron flux distribution across the radial axis and buildup uranium-233. Figures 3.2 and 3.3 show the top and side views of the TRIGA reactor modeled in MCNPX.

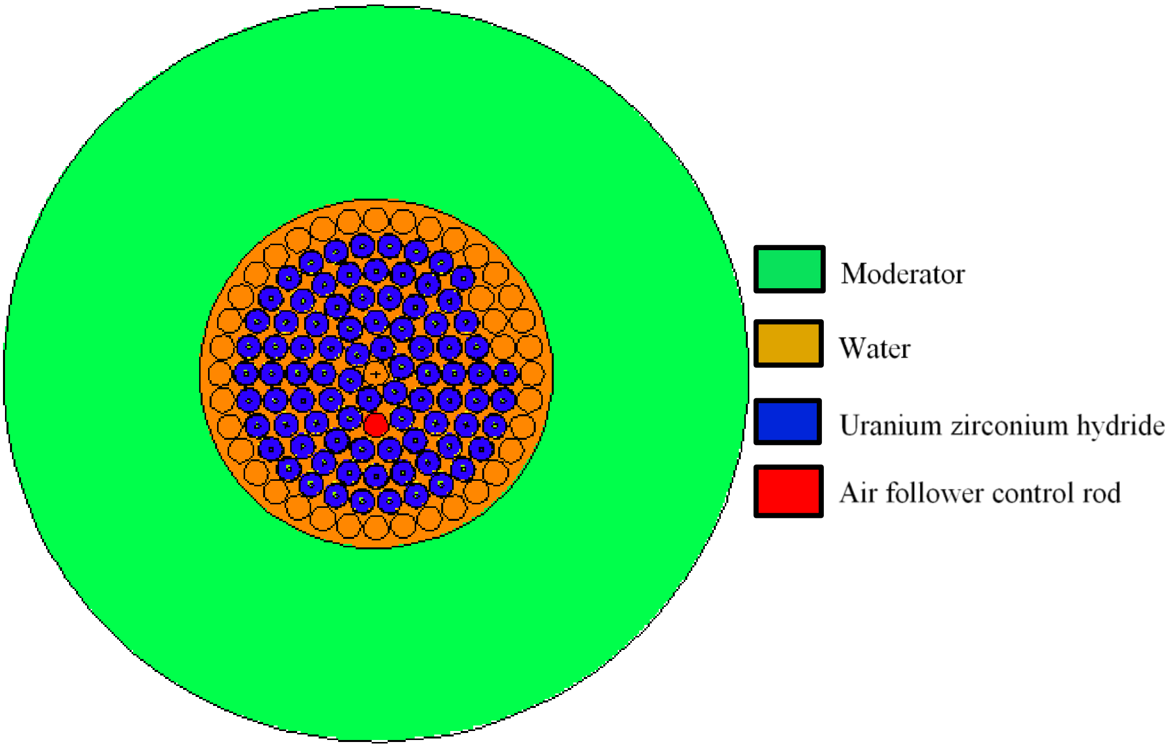


Figure 3.2: Cross section core #1 TRIGA reactor from the top view in MCNPX

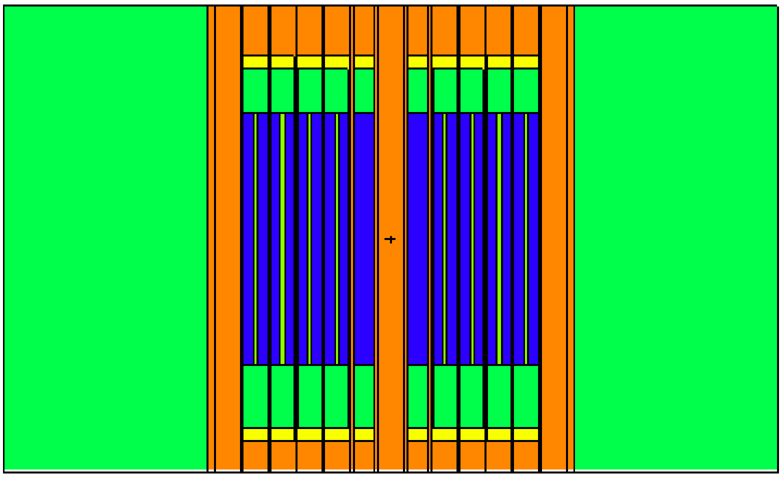


Figure 3.3: Cross section of core #1 TRIGA reactor from the side view

There are several reasons why the usage of thorium zirconium hydride fuel is selected instead of pure thorium fuel. The first one is that the fuel material needs to be similar material as the existing core to avoid any chemical compatibility issue. Next, the value of discharge burnup of thorium hydride fuel (191.8 MWd/kg) is higher than the pure thorium fuel (79.8 MWd/kg). Besides, the discharge burnup for thorium oxide is also lower than the value of thorium hydride, as shown in Table 3.1.

Table 3.1: Attainable thorium burnup in spectrum softened blanket and corresponding thorium utilization relative to the utilization of natural uranium in LWRs [37]

System	Discharge burnup MWd/kg	Fuel utilization in MWd/kg relative to	
		LEU feed to LWRs	Natural uranium feed to LWRs
PWR reference	50	1	1
Th metal	79.8	1.6	13.5
ThO_2	109.5	2.2	18.6
$ThH_{0.5}$	191.8	3.8	32.5
ThH_2	244.6	4.9	41.5
FCM	481.5	9.6	81.6
Th metal to 400 DPA	171.6	3.4	29.1

Power density is an important parameter, and reactor operators should be familiar with the TRIGA. Generally, operators should try to maintain the reactor flux as flat or constant as possible across the reactor by cautiously loading new elements in the outer ring and gradually moving them towards the centre as the fuel is burned. Standard reactor physics calculations show that the neutron flux and local reactor power is peaked towards the centre of the TRIGA core as shown in Figure 3.4. Table 3.2 below shows the average power per element at the TRIGA core for 1 MW power.

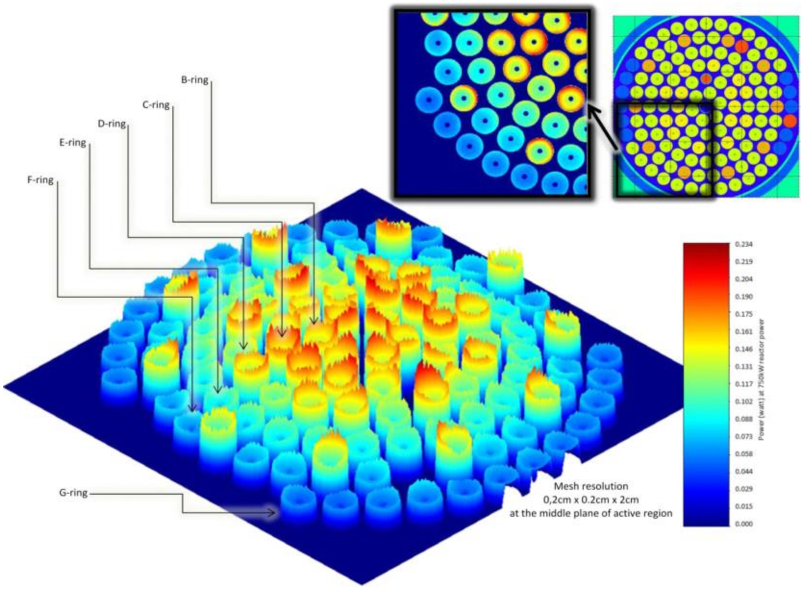


Figure 3.4: Power peaked in RTP [34]

Table 3.2: Calculated power per element [22]

B ring	C ring	D ring	E ring	F ring
18.85	14.68	12.63	9.99	9.22

Data above show the power of each fuel increasing towards the centre of the core. To calculate power peaking factors, the maximum power of fuel element needs to be divided with the average power of the fuel element. Table 3.3 shows the calculation for power peaking factor.

Table 3.3: Power peaking factor [22]

Maximum power per element, P_{max}	Minimum power per element, P_{min}	Average power per element, P_{ave}	P_{max}/P_{min}	P_{max}/P_{ave}
15.85	9.22	11.24	1.72	1.41

3.2.1 Core-01:- Addition of Thorium Fuel to Core-01 Configuration

There are ten variants of core design with thorium fuels, as shown in Table 3.4. The cores are designed based on core #1 with the addition of thorium zirconium hydride fuel rods. Each design is labelled with A, B, C, D, E, F, G, H, I and J. The number of thorium fuel rods increases by two rods from configuration A to configuration J. Table 3.4 below shows the number of thorium fuel for each configuration.

Table 3.4: No of fuel rods in Core-01

Configuration	$U\text{-}ZrH_{1.6}$ fuels	$Th\text{-}ZrH_{1.6}$ fuels	Total fuels ($U\text{-}ZrH_{1.6}$ + $Th\text{-}ZrH_{1.6}$)
Core-01A	86	2	88
Core-01B	86	4	90
Core-01C	86	6	92
Core-01D	86	8	94
Core-01E	86	10	96
Core-01F	86	12	98
Core-01G	86	14	100
Core-01H	86	16	102
Core-01I	86	18	104
Core-01J	86	20	106

For each of the configuration, all of the factors such as criticality, flux distribution, burnup calculation, and buildup uranium-233 are being identified. The power of the reactor is set at 1 MW, which is the maximum power of PUSPATI TRIGA Reactor throughout the cycle. The duration of burnup is 500 hours for each running cycle. Every week, the reactor operates for 5 hours per day from Monday to Thursday. The calculation below shows the exact time for the time reactor operate.

$$Simulation\ time\ for\ one\ configuration = \ 1000\ days \tag{3.3}$$

$$\text{Operational time RTP daily} = \ 5\ \text{hours/day} \tag{3.4}$$

$$\text{Real time} = \frac{\text{simulation time}}{\text{operational time}} \tag{3.5}$$

$$\text{Real time} = \frac{(1000\ \text{days}\ \times 24\ \text{hours/day})}{(5\ \text{hours/day})} \tag{3.6}$$

Since, real time = 4800 days RTP operational time

$$\because\ \text{RTP operation time} = 4\ \text{days/week} \tag{3.7}$$

$$\therefore\ \text{Time for one simulation} = \frac{4800\ \text{days}}{4\,\frac{\text{days}}{\text{week}}} = 1200\ \text{weeks}\ \approx 276\ \text{months} \approx 23\ \text{years}$$

Based on the equations above, it is estimated that the burnup duration for each simulation equivalent to 23 years of operational for PUSPATI TRIGA Reactor. Figures 3.5 and 3.6 show the cross section of Core-01J, which has 20 fuels of thorium rods.

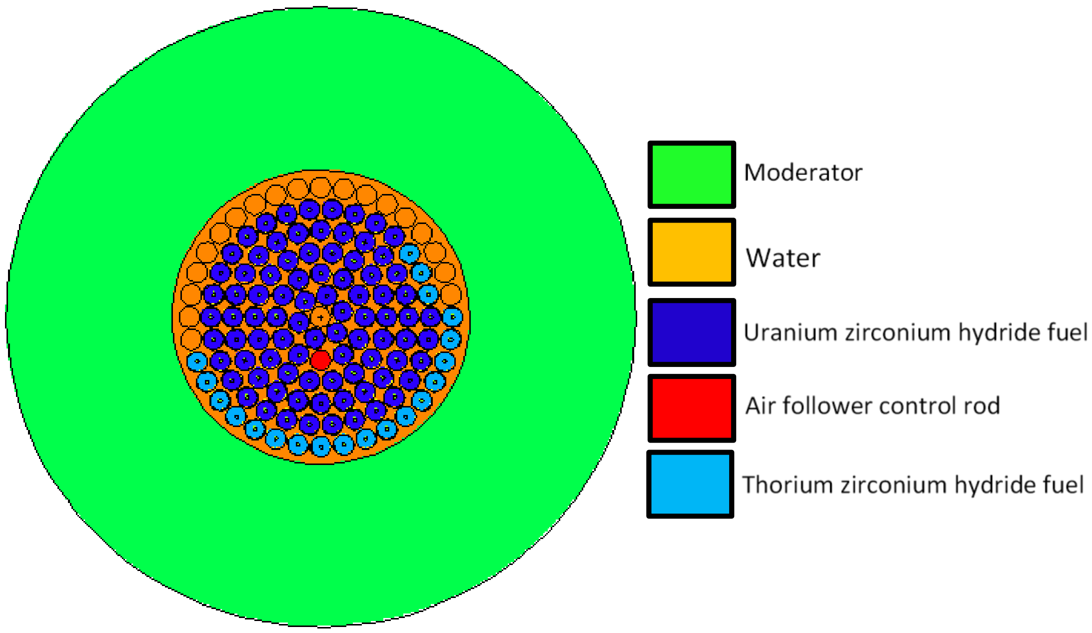


Figure 3.5: Cross section of Core-01J from top view in MCNPX

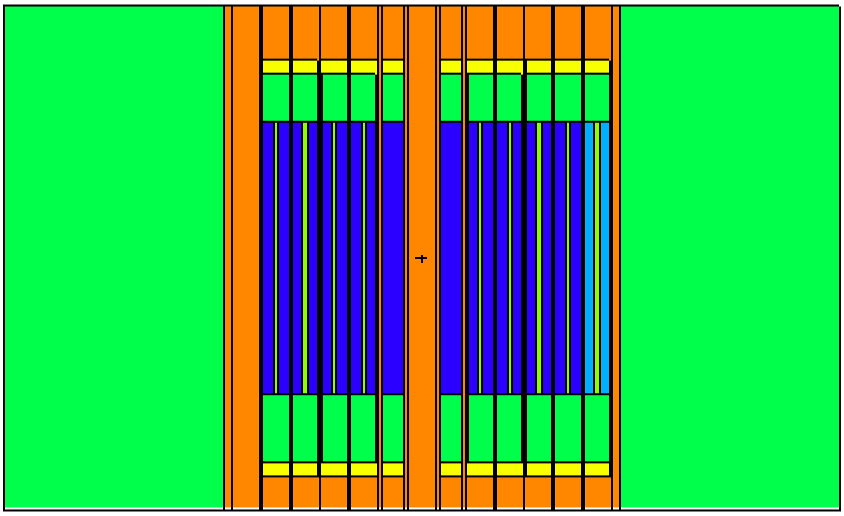


Figure 3.6: Cross section of Core-01J from the side view

3.2.2 Core-02:- Replacement of Uranium Fuel with Thorium Fuel in Ring F

The fuel rods inside the core are arranged according to core #1 configuration of PUSPATI TRIGA reactor. Then, the core consists of 86 U-$ZrH_{1.6}$ fuel rods with 8.5wt.% of uranium-235 is replaced with thorium fuel rods Th-$ZrH_{1.6}$ in ring F. The core is designed such as with the addition of two thorium fuel rods, two rods of U-$ZrH_{1.6}$ is subtracted from each core resulting total of 86 thorium and uranium fuel rods combines. Table 3.5 shows the details for core-02, and Figure 3.7 shows the arrangement of Core-02I. All parameters that have been identified in step 2 are observed in this step.

Table 3.5: No of fuel rods in Core-02

Configuration	U-$ZrH_{1.6}$ fuels	Th-$ZrH_{1.6}$ fuels	Total fuels (U-$ZrH_{1.6}$ + Th-$ZrH_{1.6}$)
Core-02A	84	2	86
Core-02B	82	4	86
Core-02C	80	6	86
Core-02D	78	8	86
Core-02E	76	10	86
Core-02F	74	12	86
Core-02G	72	14	86
Core-02H	70	16	86
Core-02I	68	18	86
Core-02J	66	20	86

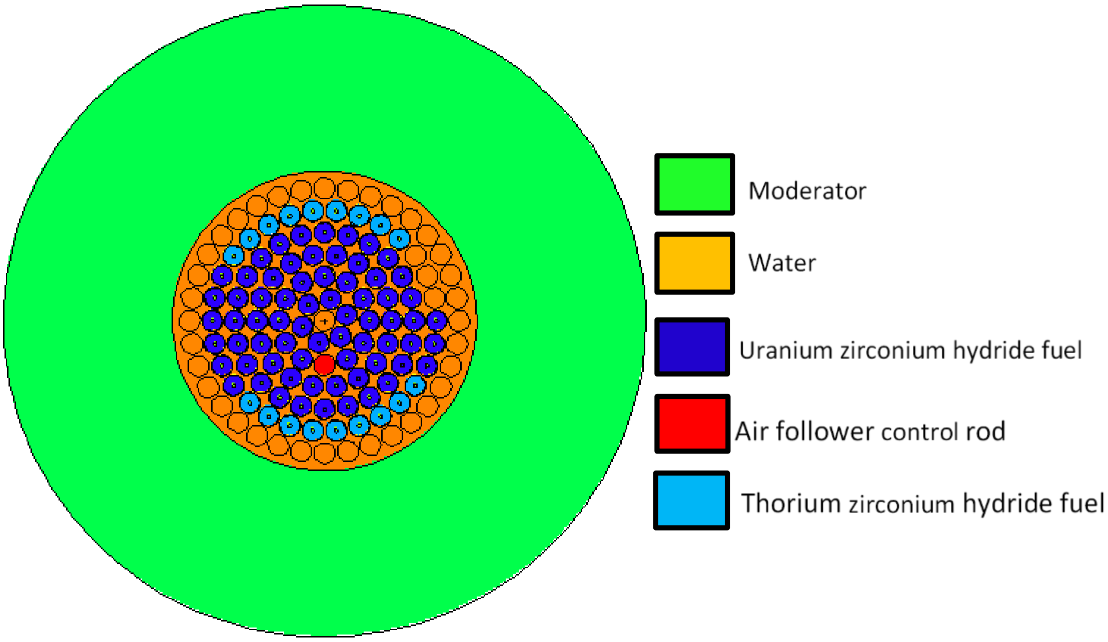


Figure 3.7: Core-02I configuration

3.2.3 Core-03:- Seed-blanket Unit Configuration

The fuel rods are arranged with a seed-blanket unit configuration. The thorium fuels are placed in the outermost ring of the core, and they are arranged adjacent to each other. The numbers of fuel rods are the same with previous configuration with 86 rods for U-$ZrH_{1.6}$, and the maximum amount of thorium rods are 20 rods. Table 3.6 shows the number of fuel rods in core-03. In this configuration, the uranium fuel act as the seed to give neutron for blanket, which is thorium fuel. Figure 3.8 shows the configuration of a seed blanket unit for Core-03J.

Table 3.6: No of fuel rods in Core-03

Configuration	$U\text{-}ZrH_{1.6}$ fuels	$Th\text{-}ZrH_{1.6}$ fuels	Total fuels ($U\text{-}ZrH_{1.6}$ + $Th\text{-}ZrH_{1.6}$)
Core-03A	86	2	88
Core-03B	86	4	90
Core-03C	86	6	92
Core-03D	86	8	94
Core-03E	86	10	96
Core-03F	86	12	98
Core-03G	86	14	100
Core-03H	86	16	102
Core-03I	86	18	104
Core-03J	86	20	106

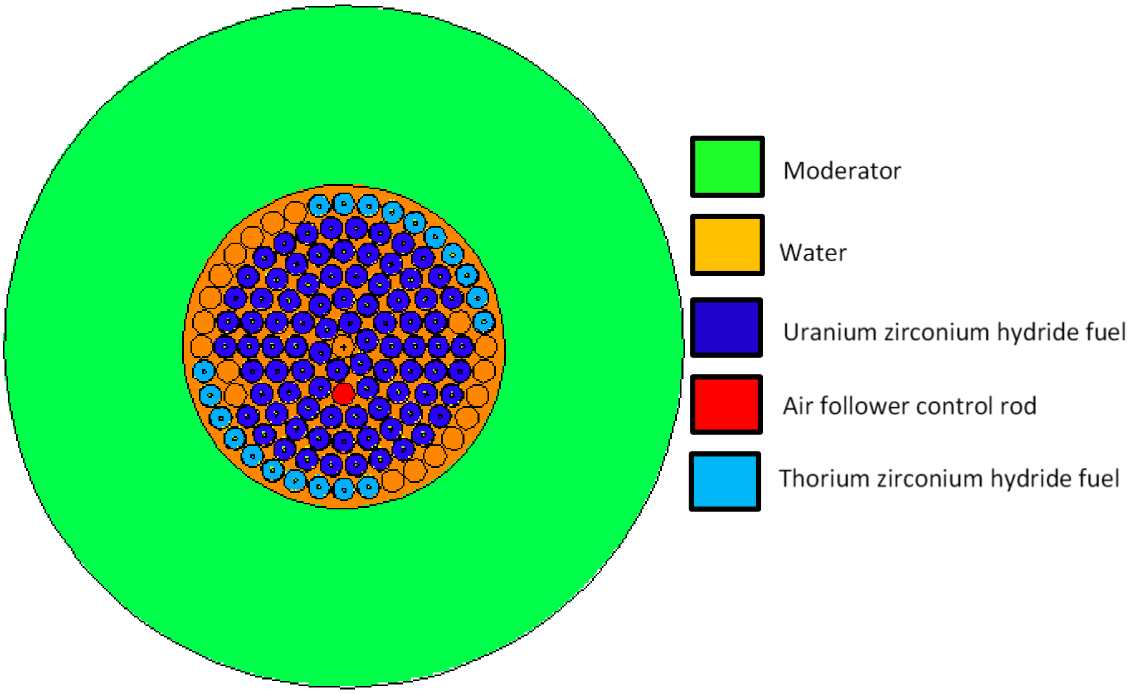
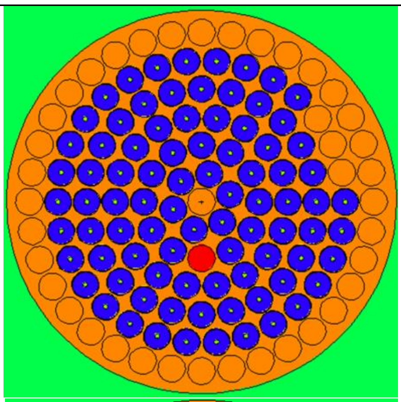
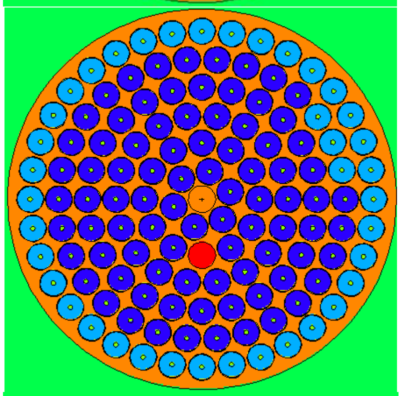
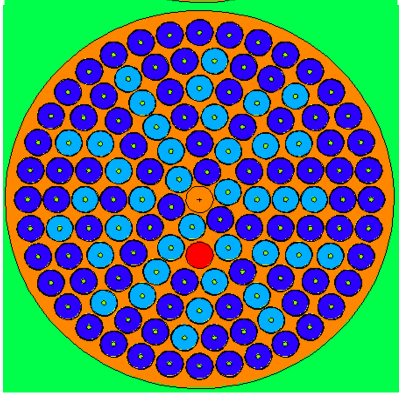


Figure 3.8: Core-03J configuration

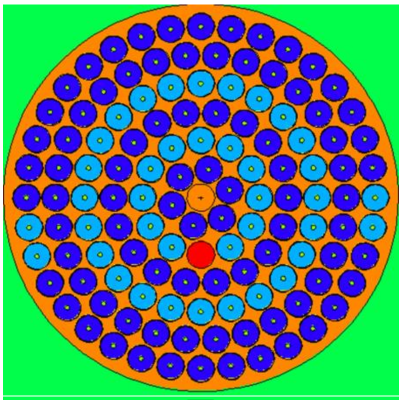
3.3 Different Core Arrangement

A new set of core configurations have been designed and modeled to different fuel arrangements. Table below shows the different arrangements that have been introduced to the core of RTP.

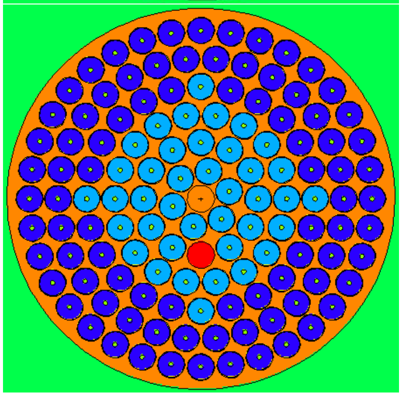
Table 3.7: List of arrangements of configuration

Configuration	Figure
A	
B	
C	

D



E



*Colour labeling follow Figure 3.7

Configuration A shows the core with 86 number of U-$ZrH_{1.6}$ the core is the same design with the real core of RTP, which is the Core 0. It is the first core that reaches the criticality with the number of k_{eff} 1.05261 and consists of 82 full solid U-$ZrH_{1.6}$ fuel, and 4 control rod which 3 of the rods are fuel follower control rods and 1 of it is air follower control rods. The core is filled with water, which also acts as a moderator.

For configuration B, the blank space in the core is filled with thorium fuels. The thorium fuels are arranged at the outermost and second outermost rings of the core as an imitation of a seed-blanket configuration. 86 rods of U-$ZrH_{1.6}$ are arranged in the middle of the core surrounded by 39 numbers of thorium fuels.

Configuration C shows the arrangement of RTP core with a checker configuration. Thorium fuels are arranged in the middle of the core with 3 of the thorium fuels placed in ring B, 6 in ring C, 9 in ring D, 12 in ring E and 9 in ring F. Thorium fuels are arranged in a checker box-like configuration.

Next one is configuration D, which has thorium fuels arranged only in specific rings of the core. The fuel is arranged alternately with $UZrH_{1.6}$. 11 thorium fuel rods are arranged in ring C, 24 rods in ring E and another 4 rods are in ring G.

Lastly, for configuration E, the thorium fuel rods are arranged in the middle of the core with a diamond shape arrangement. Most of the rods are situated in ring B, C, D and 4 of the rods in ring E.

3.4 Parametric configuration

Based on the different configurations in Table 3.7, the cores are simulated with different parametric conditions. The first condition is the mass of thorium. Except for configuration A, thorium fuel rods are added by 2, 20 and 39 rods in configuration B, C, D, and E. The cores are then simulated using MCNPX.

As for the thorium fuel rods added, the number are in 2, 20 and 39 to determine three level of thorium in the core. The core that added with 2 thorium fuel rods represent the lowest amount of thorium in the core, while the core with 20 thorium fuel rods are the intermediate level for thorium. As for 39 thorium fuel rods, the cores are in highest level for thorium fuels. Thorium fuel rods are added to 39 rods and not to 40 because of the maximum number fuel rods that can be added in the core are 39 rods. Therefore, in order to give the similar result, the core with 39 thorium fuel rods are created.

Another condition that is changed for the simulation is the power of the reactor. According to the RTP safety analysis report, the operational power of RTP is 750 kW, and the maximum power of the core is 1 MW [16] while the highest power that a TRIGA reactor manages to achieve is 3 MW. Configuration A, B, C, D, and E are simulated with different power levels, which are 0.75 MW, 1 MW and 3 MW.

Lastly, the final condition that was investigated for the simulation is the type of thorium fuel added to the core. The first fuel is thorium zirconium hydride (Th-

$ZrH_{1.6}$) that has the same fuel material operated in RTP, namely $UZrH_{1.6}$. Next material is thorium oxide, which is used widely in the thorium industry such as in thorium salt reactor. Lastly, the fuel that has been simulated is pure thorium element.

3.4.1 Mass

For analyzing the mass effect, 12 configurations were designed and simulated with each main configuration has different arrangements and amount of thorium fuels. Starting with configuration B, C, D, and E, the minimum number of thorium fuel is 2 and the maximum number of thorium fuels is 39 fuel rods. Each configuration is labelled with B2, B20 and B39 for configuration B. Configuration C consists of C2, C20 and C39 while configuration D with D2, D20 and D39 and configuration E with E2, E20 and E39. The numbers beside the label represent the total number of fuel rods in the core. Configuration A is not investigated based on the mass parameter because the core is in the original state.

3.4.2 Reactor Power

There are 15 simulated configurations starting with configuration A, B, C, D, and E. Each of them has a different arrangement of the fuel core and reactor power. The core configurations are labeled with A0.75, A1, A3, B0.75, B1, B3, C0.75, C1, C3, D0.75, D1, D3, E0.75, E1, and E3. The numbers beside each label indicate the power of the reactor core. The minimum power of the core is 750 kW, and the highest power of the core is 3 MW.

3.4.3 Thorium Fuel

Lastly, 12 configurations have different types of thorium fuel and arrangement of the fuel core that have been simulated. There are three types of thorium fuel which are thorium zirconium hydride, thorium oxide and pure thorium fuel. Configuration B, C, D, and E are set to have different thorium fuel with the label of Bo, Bz, Bt, Co, Cz, Ct, Do, Dz, Dt, Eo, Ez and Et where the letter ‘o’ represent ThO_2, letter ‘z’ stand for Th-$ZrH_{1.6}$ and letter ‘t’ for pure thorium fuel. Configuration A is not simulated because the core is in the original state.

Figure 3.9 shows the summary for all configurations that have been designed beginning from core #1 to the addition of thorium fuels for core-01 to core-03 until the different sets of designed configurations.

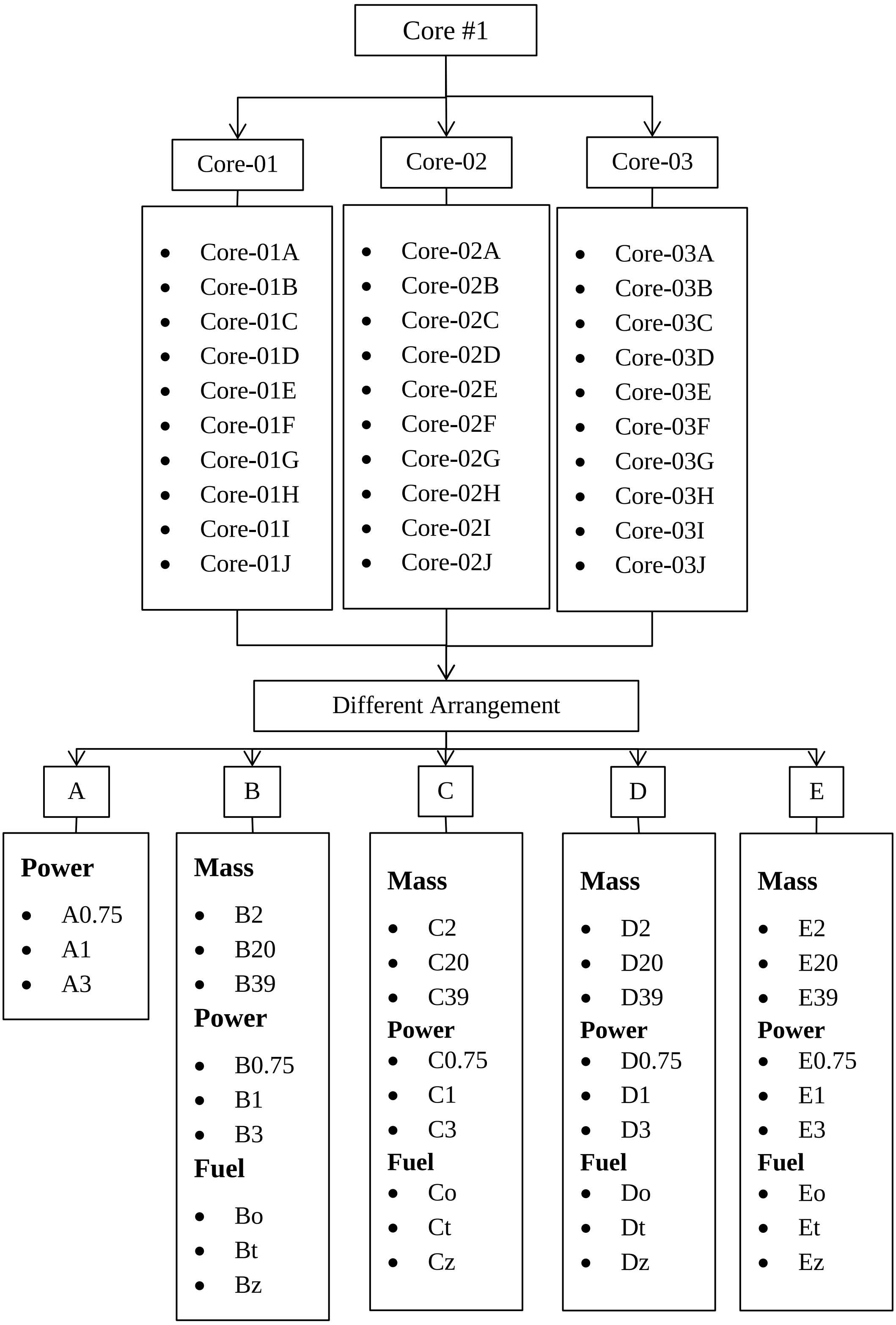


Figure 3.9: Summary of all configuration

CHAPTER 4

RESULTS AND DISCUSSION

4.1 The Basic Configuration Reactor Core

The designed cores have been simulated using MCNPX with 10000 neutrons in a cycle with 550 cycles. The simple simulation focused on the beginning of the cycle (BOC) of the configuration. Therefore, there is no burnup calculation result. Table 4.1 shows the result obtained from the BOC of the configuration.

Table 4.1: Simulated k_{eff} of the designed core 1 (BOC)

Configuration	Criticality, k	Reactivity difference (pcm x10^5) from configuration Core #1
k_{eff} simulated (Core #1)	1.05139	0
k_{eff} Core-1	1.05677 [14]	0.00484
k_{eff} Core-11	1.07517 [12]	0.02104
k_{eff} Core-15	1.0364 [39]	0.013757

A preliminary simulation was conducted on core-#1 to determine the value of k_{eff} at the beginning of the cycle (BOC). The result shows that k_{eff} for BOC of core #1 is 1.05139. Furthermore, Table 4.1 shows the result of simulated BOC for the core that has been conducted by the previous study. According to the result, it shows that the designed core has almost the same value k_{eff} compared with the previous study with the PCM of 484, 2104 and 1375.7. Therefore, it can be accepted with the real core of RTP.

4.1.1 Core-01

Core-01 is the core that has been added with thorium. The thorium is added to the core with different numbers of thorium rods. Table 4.2 shows simulation results that have been obtained from 10 sets of Core-01 with each of them has 550 cycles and 10000 neutrons.

Table 4.2: Simulation result core-01

Configuration	k_{eff} Beginning of cycle (BOC)	k_{eff} Lifecycle (days)	k_{eff} Slope	Buildup uranium-233 at the EOC (g)	Standard Deviation
Core #1	1.0521	532	-0.00014	0	0.0034
Core-01A	1.0517	533	-0.00014	1.02	0.0033
Core-01B	1.05141	533	-0.00014	1.86	0.0032
Core-01C	1.05129	522	-0.00014	2.57	0.0034
Core-01D	1.05106	524	-0.00014	3.36	0.0032
Core-01E	1.05096	523	-0.00014	4.15	0.0035
Core-01F	1.0509	522	-0.00014	4.94	0.0035
Core-01G	1.0509	522	-0.00014	5.76	0.0034
Core-01H	1.05036	520	-0.00014	6.62	0.0034
Core-01I	1.05021	517	-0.00013	7.44	0.0035
Core-01J	1.05086	518	-0.00013	8.31	0.0032

According to the Table 4.2, it shows that all the k_{eff} from BOC are in the range of 1.05000, which is slightly supercritical. When going toward at the end of the cycle, the k_{eff} starts to decline to the average value of 0.98000. This is due to the depleted fuels that have been undergoes burnup process.

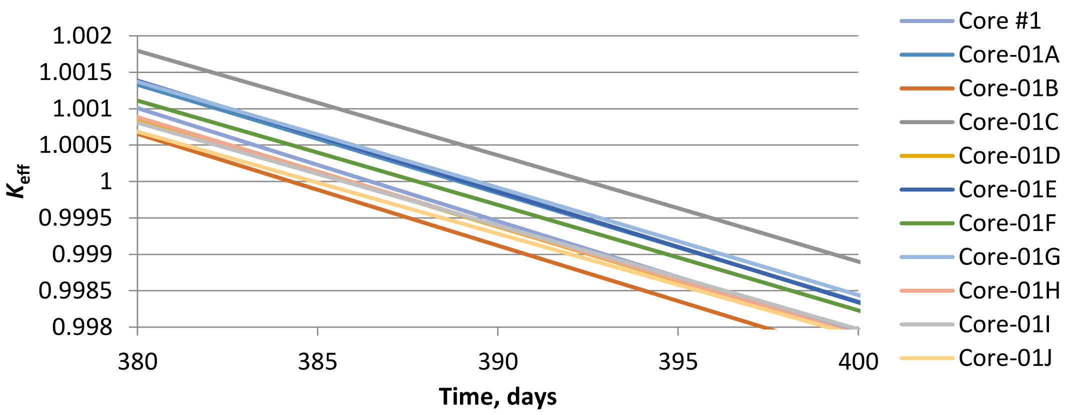


Figure 4.1: k_{eff} value for core-01

Figure 4.1 shows the trend line of core-01 from the beginning of the cycle to the end of the cycle. The graph shows that all configurations have the same plot pattern with a decreasing value at the end of the cycle. The slope of the graph is in the value of -0.00014 for almost all the graph. This is because the value of thorium does not give significant result to the criticality of the core. That is why the slope of the graph give almost the same result.

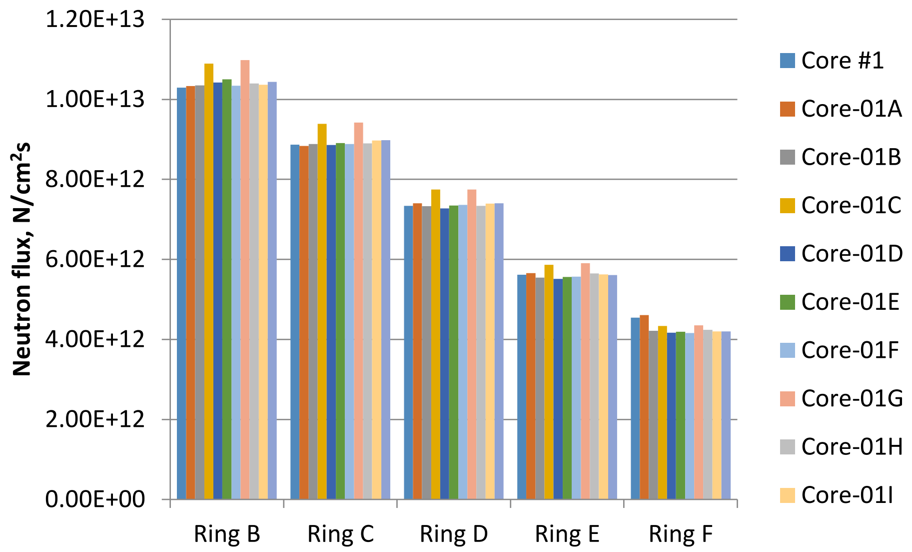


Figure 4.2: Thermal neutron flux core-01

Figure 4.2 above shows the value of thermal neutron flux for core-01. The graph shows the decreasing trend of thermal flux from the center of the core (ring b) toward the outside of the core (ring f). The distribution of flux shows that it is highest at the centre of the core. This is because the fissile element (uranium 235) situated at the centre of the core resulting the increasing value of neutron flux at the centre toward outside of the core.

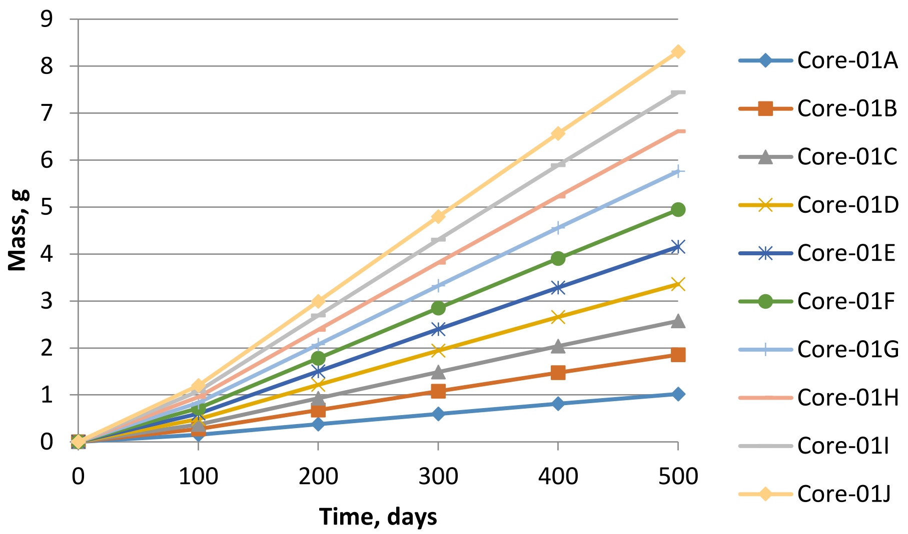


Figure 4.3: Buildup uranium-233 core-01

Figure 4.3 shows the production of uranium-233 in core-01. It shows that the mass of uranium-233 increases as the number of thorium rod increases for a different configuration. The highest value of uranium-233 that has been produced at the end of cycle is from core-01J, with the mass of 8.31 gram. Due to the increasing value of thorium fuel rods in each configuration, the value of uranium-233 increasing when the volume of thorium increases.

4.1.2 Core-02

Core-02 is designed by replacing U-$ZrH_{1.6}$ fuel rods with of thorium rods. For each configuration, two rods of thorium are added, and two U-$ZrH_{1.6}$ fuel rods are removed from the core. The value of cycles and neutrons per second are the same with simulation core-01 which 550 cycles and 10000 neutrons per second. Table 4.3 shows the results that have been obtained for simulation core-02.

Table 4.3: Simulation result core-02

Configuration	k_{eff}			Buildup uranium-233 at the EOC (g)	Standard Deviation
	Beginning of cycle (BOC)	Lifecycle (days)	Slope		
Core #1	1.0521	532	-0.0001378	0	0.0033
Core-02A	1.04621	477	-0.0001398	1.095	0.0033
Core-02B	1.04107	430	-0.0001563	2.141	0.0034
Core-02C	1.03566	372	-0.0002200	3.162	0.0035
Core-02D	1.031175	372	-0.0001496	4.2115	0.0034
Core-02E	1.02669	141	-0.0001690	5.261	0.0035
Core-02F	1.02151	114	-0.0001731	6.362	0.0033
Core-02G	1.01598	88.5	-0.0001770	7.518	0.0034
Core-02H	1.01087	63	-0.0001809	8.778	0.0035
Core-02I	1.00531	34.5	-0.0001884	10.06	0.0033
Core-02J	0.99884	-	-0.0000718	11.43	0.0033

It shows that almost all configurations are in a slightly supercritical state at BOC with only one configuration is subcritical, namely core-02J. The slope of the graph shows that core-02J has the steepest slope among all of the configuration with the value of -0.0000718. This is because the presence of U-$ZrH_{1.6}$ is insufficient in the core in order to become supercritical.

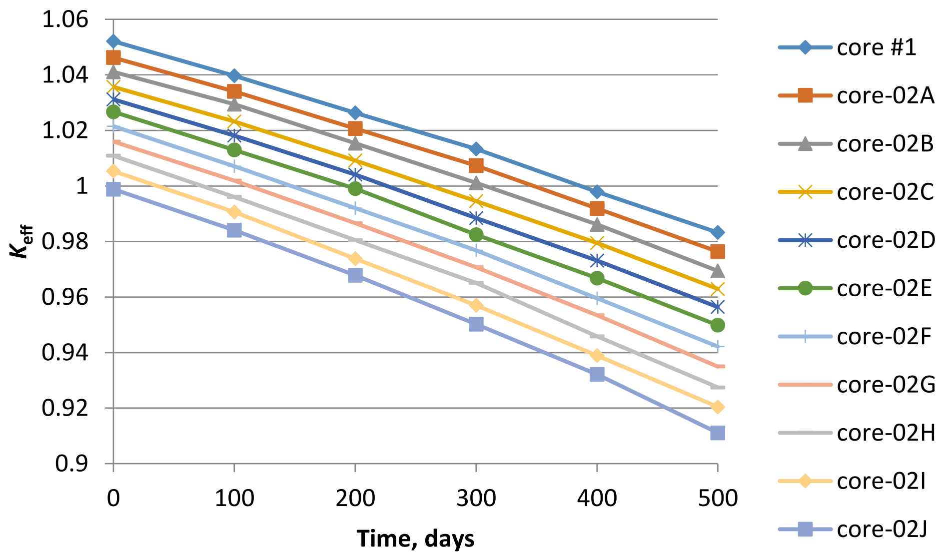


Figure 4.4: k_{eff} value for core-02

Figure 4.4 above shows the value of k_{eff} for ten different configurations with core #1 as a reference. It shows the same pattern with core-01, which is decreasing in time from BOC toward EOC. The lowest value of k_{eff} is in core-02J, which maintains at the lowest part of the graph. This is due to the lower amount of uranium fuel rods in the core that leads to a lower number of k_{eff}. This is due to the fissile element that present in the core decreases from core-02A until core-02J.

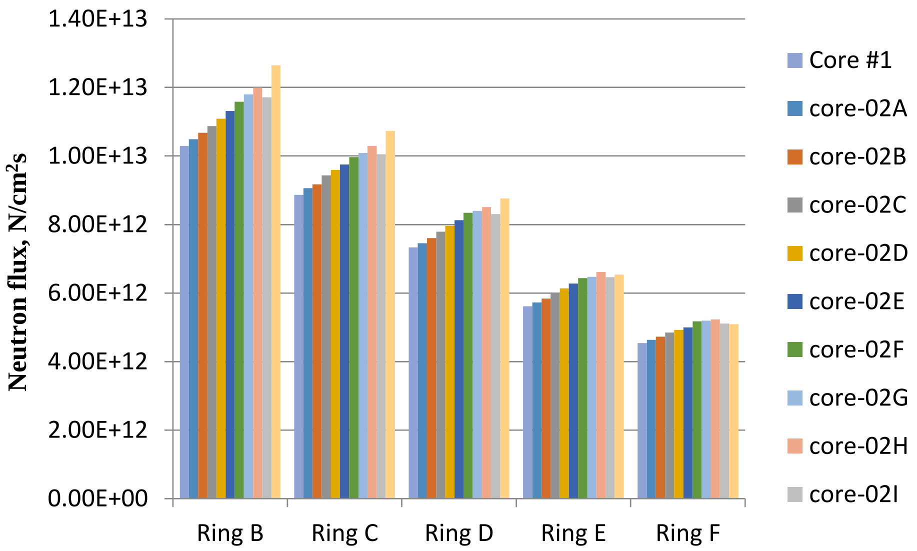


Figure 4.5: Thermal neutron flux core-02

Figure 4.5 shows the value of thermal neutron flux for core-02 that decreases from the centre of the core to the outermost part of the core. The value for each configuration is increasing for each ring structure. In ring b, for example, the value of flux increases with a different configuration. Although core-02J have the least amount of uranium fuel, it has the highest value of thermal flux at ring b and ring c which are 1.26 $\times 10^{13}$ n/cm^{2}s and 1.07$\times 10^{13}$ n/cm^{2}s respectively. This is because the value of absorption cross-section for thorium is increasing compare to decreasing value absorption cross-section for uranium. This lead to increasing number of neutron and affect the value of neutron flux in the core.

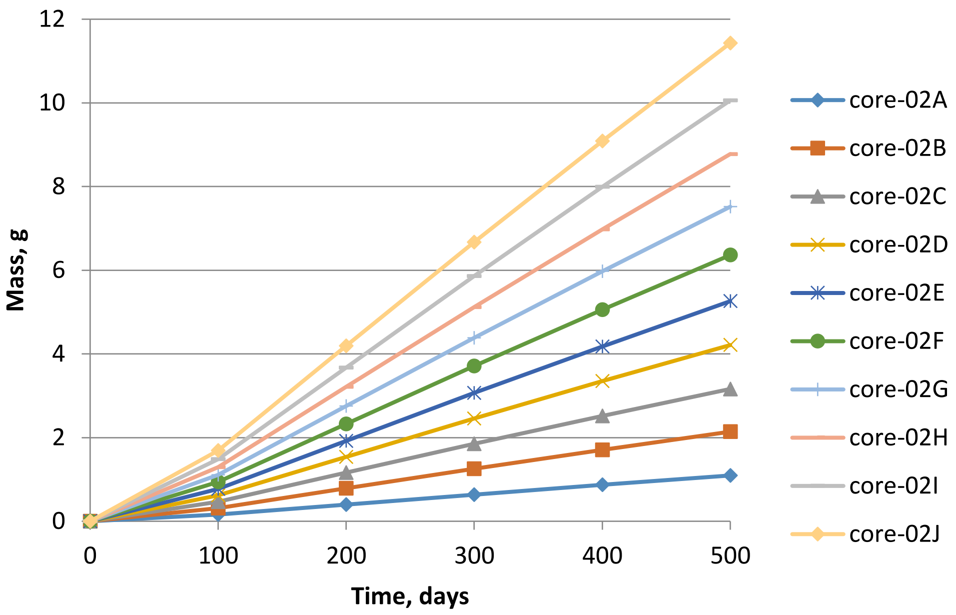


Figure 4.6: Buildup uranium-233 core-02

From Figure 4.6, it shows core-02J has the highest production of uranium-233 at EOC with the value of 11.43 gram. This also because of the number of thorium fuel rods increase for each core.

4.1.3 Core-03

Next configuration is core-03, which is the seed-blanket configuration. Uranium fuel is placed at the center of the core that will act as a seed while thorium fuel is placed surrounding the uranium fuel and act as a blanket. The neutrons per second in this simulation are constant with 10000 neutrons per second, and 550 cycles. Table 4.4 shows the simulation result for core-03.

Table 4.4: Simulation result for core-03

Configuration	k_{eff}			Buildup uranium-233 at the EOC (g)	Standard Deviation
	Beginning of cycle (BOC)	Lifecycle (days)	Slope		
Core #1	1.0521	532	-0.0001378	0	0.0034
Core-03A	1.0486	501	-0.0001361	0.84	0.0035
Core-03B	1.05215	531	-0.0001391	1.63	0.0035
Core-03C	1.05215	532	-0.0001385	2.39	0.0032
Core-03D	1.05196	531	-0.0001389	3.15	0.0034
Core-03E	1.05163	528	-0.0001383	3.94	0.0035
Core-03F	1.05092	521	-0.0001362	4.73	0.0034
Core-03G	1.05047	519	-0.0001352	5.53	0.0035
Core-03H	1.05154	523	-0.0001377	6.37	0.0035
Core-03I	1.05109	521	-0.0001358	7.20	0.0035
Core-03J	1.05135	522	-0.0001364	8.04	0.0033

Table 4.4 shows the simulation result for core-03. The k_{eff} values that have been obtained from the simulation show almost the same result with core-01 with an average k_{eff} of 1.05000. This might be due to the numbers of thorium and uranium fuels are similar to core-01, but the fuel arrangements are different. However, the slope of the graph is slightly different with core-01 as the average value for core-03 is -0.00013 while for core-01 it is -0.00014.

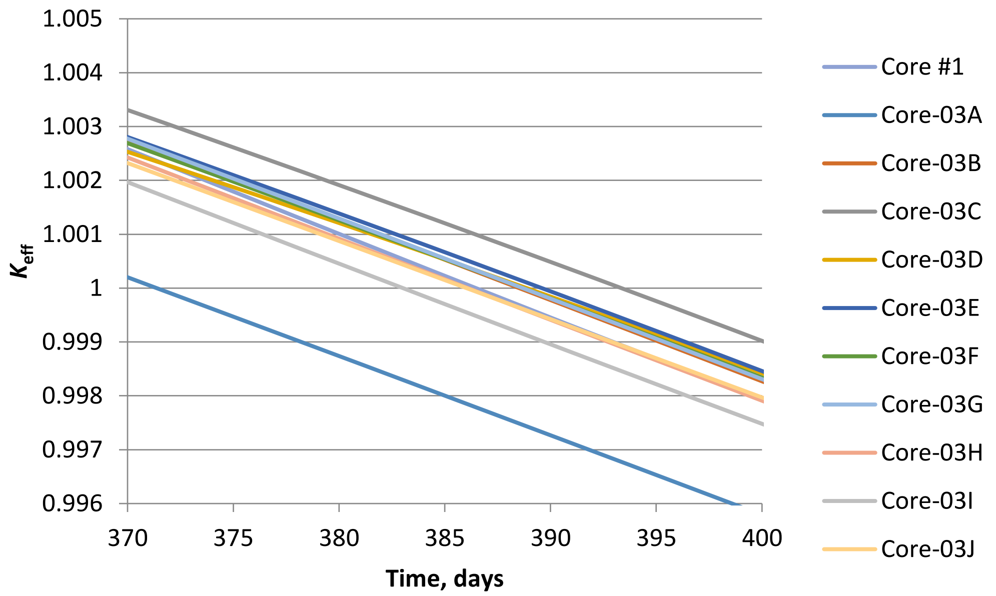


Figure 4.7: k_{eff} value for core-03

From Figure 4.7, the slope of the lines declines with time. Core-03A shows the lowest value of k_{eff} that remain at the lowest part of the graph from BOC to EOC. By referring to the graph above, although there is a big gap between core-03A and core-03I in the graph, the value of the slope between both configurations are not that big which are -0.0001361 for core-03A and -0.0001358 for core-03I. this is the same with Core 01 as the value of thorium fuel rods does not effects the value of keff.

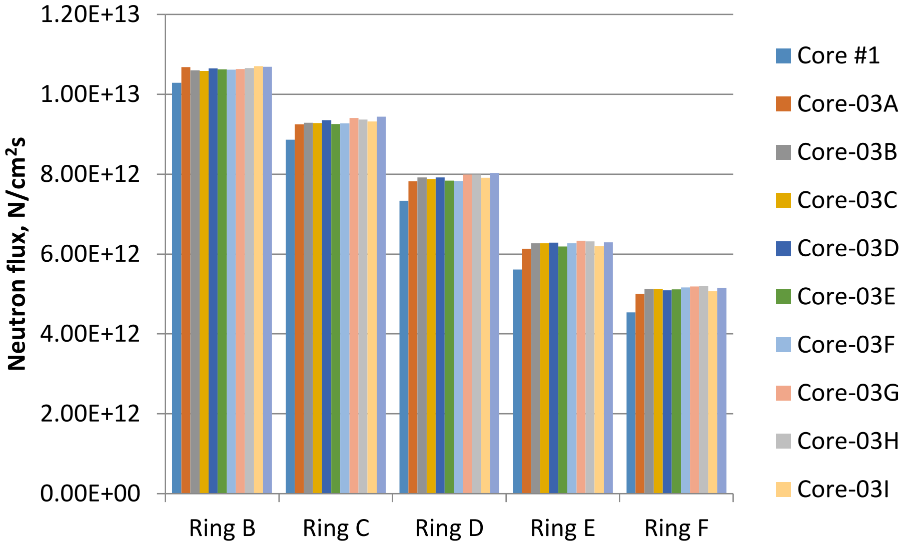


Figure 4.8: Thermal flux core-03

As for the thermal neutron flux, by referring Figure 4.8, the value for each configuration at each ring is quite constant with each other compared with core-02 that have an increasing value between each configuration in the same ring structure. The seed blanket core give the best flux distribution for the core configuration. the fission occur at the centre of the core give the highest value of thermal flux in the core.

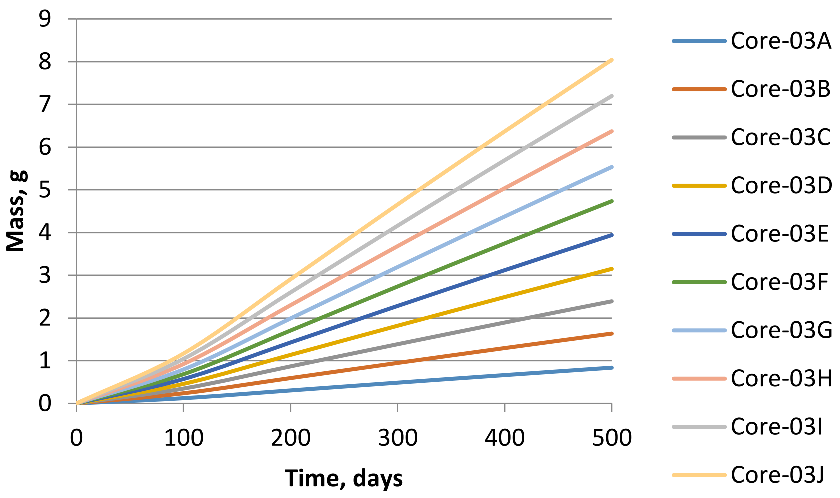


Figure 4.9: Buildup uranium-233 core-03

Lastly, the buildup of uranium-233 in core-03 is almost the same with core-01, which has the maximum value of 8.04 gram produced by configuration core-03J at the EOC. Figure 4.9 shows the maximum value of buildup uranium-233 is from core-03J, while the minimum production of uranium-233 is from core-03A. From the core-01 and core-03 results, it can be concluded that the arrangement of the fuel does not affect the result of the simulation.

4.2 Core Arrangement

4.2.1 Fuel Arrangement versus Mass of Thorium Fuels

For the next configuration, there is a total of 4 different fuel arrangements (Configurations B to E) that have been simulated for 1000 burnup days with 2500 neutrons per second and 550 cycles using MCNPX. For each arrangement, the number of thorium fuel rods is also varied to 2, 20, and 39 fuel rods, as shown in Table 4.5. The fuel that is used in the variable is thorium zirconium hydride fuels. Table 4.6 shows the result that has been obtained from the simulation.

Table 4.5: Configuration fuel arrangement versus mass of thorium fuels

Configuration	2 thorium fuels	20 thorium fuels	39 thorium fuels
A	-	-	-
B	B2	B20	B39
C	C2	C20	C39
D	D2	D20	D39
E	E2	E20	E39

Table 4.6: Simulation result fuel arrangement versus. mass of thorium fuels

Configuration	k_{eff}			Buildup uranium-233 at the EOC (g)	Standard Deviation
	Beginning of cycle (BOC)	Lifecycle (days)	Slope		
Core #1	1.0521	289	-0.00016	Core #1	0.0033
B2	1.05204	291	-0.00016	B2	0.0032
C2	0.91083	-	-0.00016	C2	0.0031
D2	0.90202	-	-0.00015	D2	0.0034
E2	0.88405	-	-0.00014	E2	0.0035
B20	1.05062	286	-0.00016	B20	0.0035
C20	0.88839	-	-0.00014	C20	0.0033
D20	0.87851	-	-0.00013	D20	0.0033
E20	0.88373	-	-0.00014	E20	0.0034
B39	1.04942	276.5	-0.00015	B39	0.0031
C39	0.86591	-	-0.00012	C39	0.0033
D39	0.86051	-	-0.00012	D39	0.0034
E39	0.87721	-	-0.00013	E39	0.0035

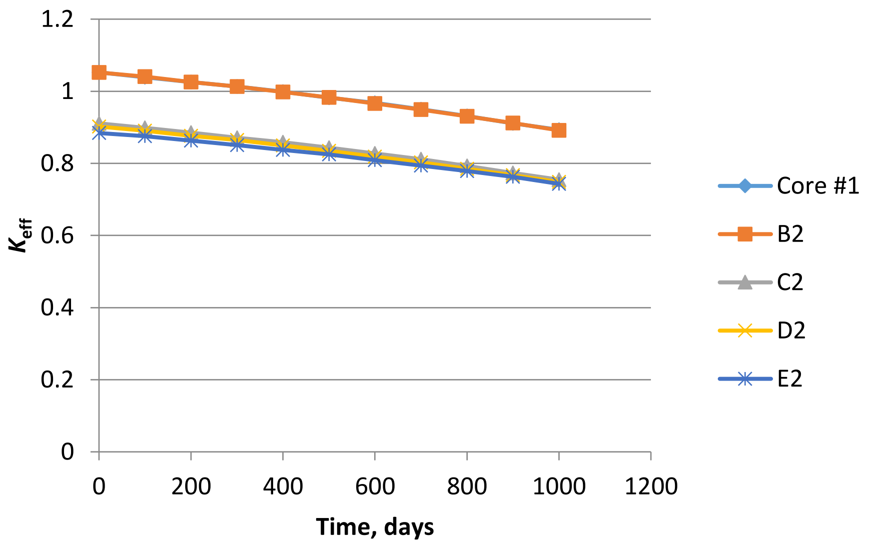


Figure 4.10: Comparison of k_{eff} for configurations with 2 thorium fuel rods.

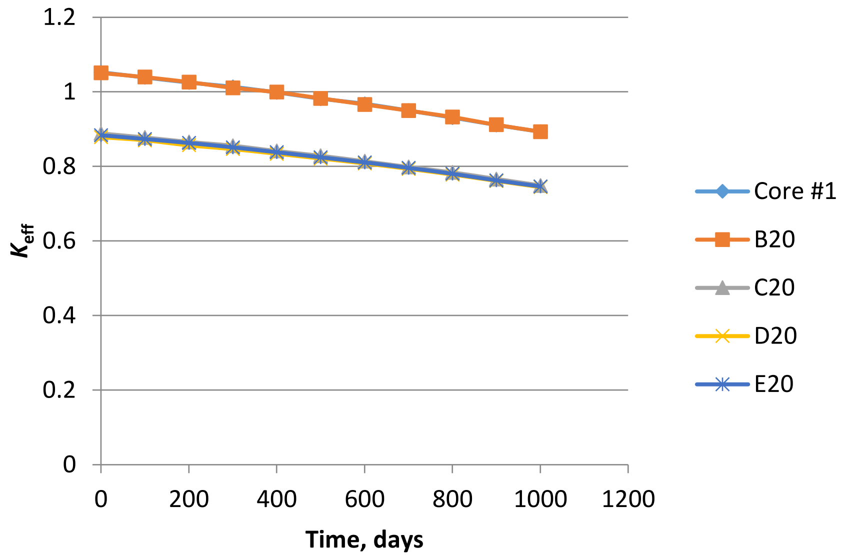


Figure 4.11: Comparison of k_{eff} for configurations with 20 thorium fuel rods.

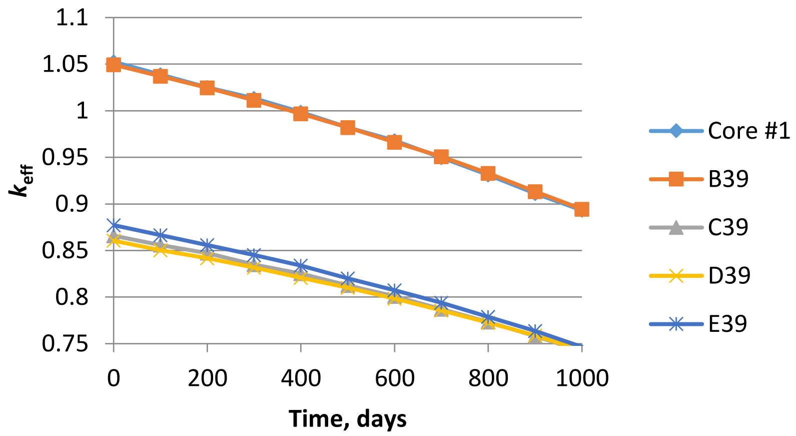


Figure 4.12: Comparison of k_{eff} for configurations with 39 thorium fuel rods.

Based on all three graphs shown, it shows that type B configuration is the best configuration in the variation of mass category. The graphs in Figures 4.10 till 4.12 show that the k_{eff} values for all type B configurations are at the top, which are quite close to the original core #1. The arrangement B has the thorium situated at the outermost side of the core. Hence, this might improve the thermal flux distribution inside the core, generating more neutrons inside the core. The value of the slope of all configurations are different from each other with the range of -0.00012 for core-C39 and core-D39 to -0.00016 for core-B2 and core-C2.

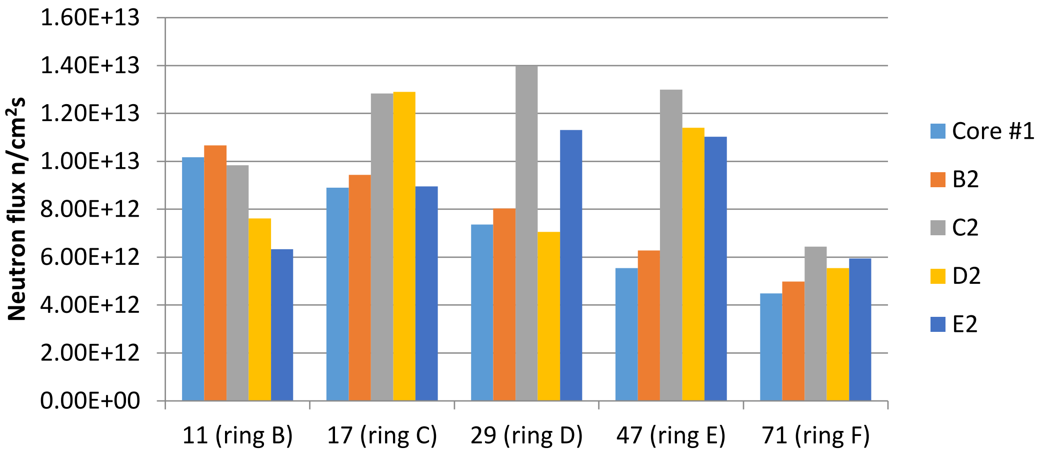


Figure 4.13: Comparison of thermal neutron flux for configurations with 2 thorium fuel rods.

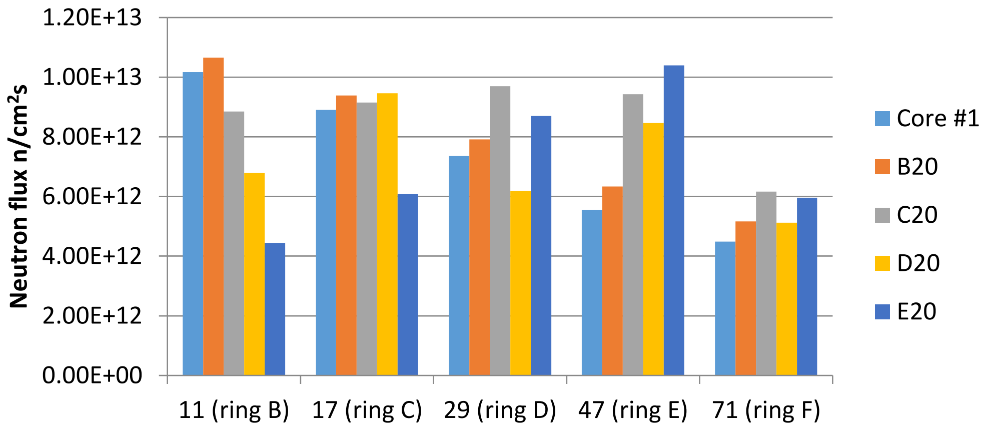


Figure 4.14: Comparison of thermal neutron flux for configurations with 20 thorium fuel rods.

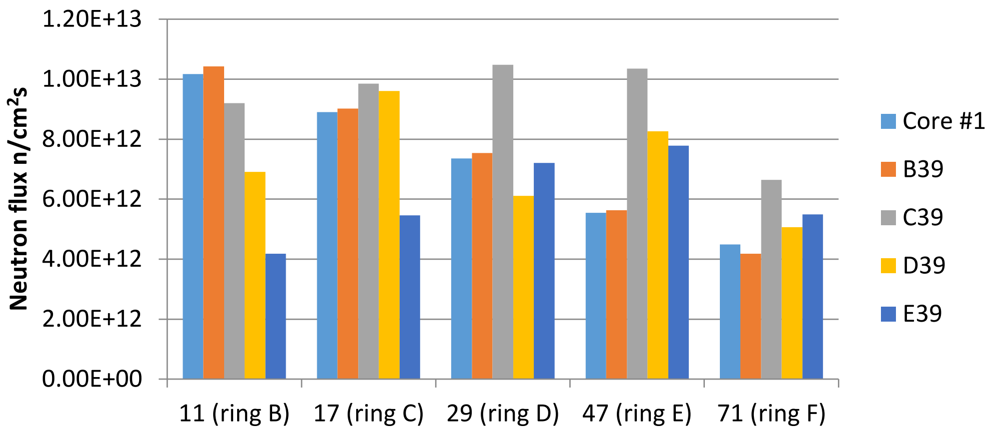


Figure 4.15: Comparison of thermal neutron flux for configurations with 39 thorium fuel rods

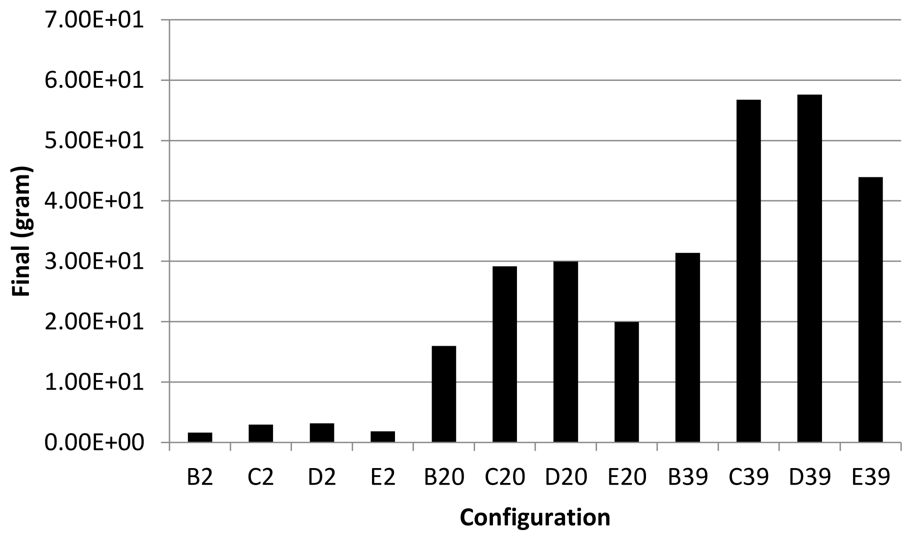


Figure 4.16: Buildup of uranium-233 fuel arrangement vs. mass of thorium fuels

Figure 4.16 above shows the buildup of uranium-233. It shows that configurations B and C have the highest mass of uranium-233 at EOC. This might be due to the neutron flux distribution in those configurations that causes the mass of uranium-233 to increase, although k_{eff} values are low.

4.2.2 Fuel Arrangement versus Reactor Power

In the next batch of simulation, five different core arrangements simulated with different three different reactor powers, namely 750 kW, 1 MW and 3 MW, as shown in Table 4.7. The mass for thorium fuel is fixed with 39 fuel rods. The table shows the label for the core arrangement of this simulation. Total 2500 neutrons per second per cycle used with a total number of 550 cycles. Th-$ZrH_{1.6}$ is the fuel used for thorium. The 1 MW power simulation result is used to compare with the results from other reactor powers.

Table 4.7: Configuration label for different reactor powers.

Configuration	750 Kw	1 MW	3 MW
A	A0.75	A1	A3
B	B0.75	B1	B3
C	C0.75	C1	C3
D	D0.75	D1	D3
E	E0.75	E1	E3

Table 4.8: Simulation result for fuel arrangement at various reactor powers.

Configuration	k_{eff}			Buildup uranium-233 at the EOC (g)	Standard Deviation
	Beginning of cycle (BOC)	Lifecycle (days)	Slope		
A0.75	1.05133	547	-0.00011	0	0.0033
B0.75	1.04934	531	-0.00011	24.05	0.0034
C0.75	0.86618	-	-0.00009	45.53	0.0034
D0.75	0.86149	-	-0.00008	46.46	0.0032
E0.75	0.87679	-	-0.00009	34.44	0.0031
A1	1.05246	289.5	-0.00016	0	0.0032
B1	1.04942	276.5	-0.00015	31.4	0.0033
C1	0.86591	-	-0.00012	56.74	0.0034
D1	0.86051	-	-0.00012	57.62	0.0034
E1	0.87721	-	-0.00013	43.96	0.0032
A3	1.05122	158.6	-0.00088	0	0.0033
B3	1.04941	165.1	-0.00083	78.09	0.0033
C3	0.86643	-	-0.00062	87.13	0.0034
D3	0.86091	-	-0.00061	87.07	0.0034
E3	0.87626	-	-0.00065	83.2	0.0035

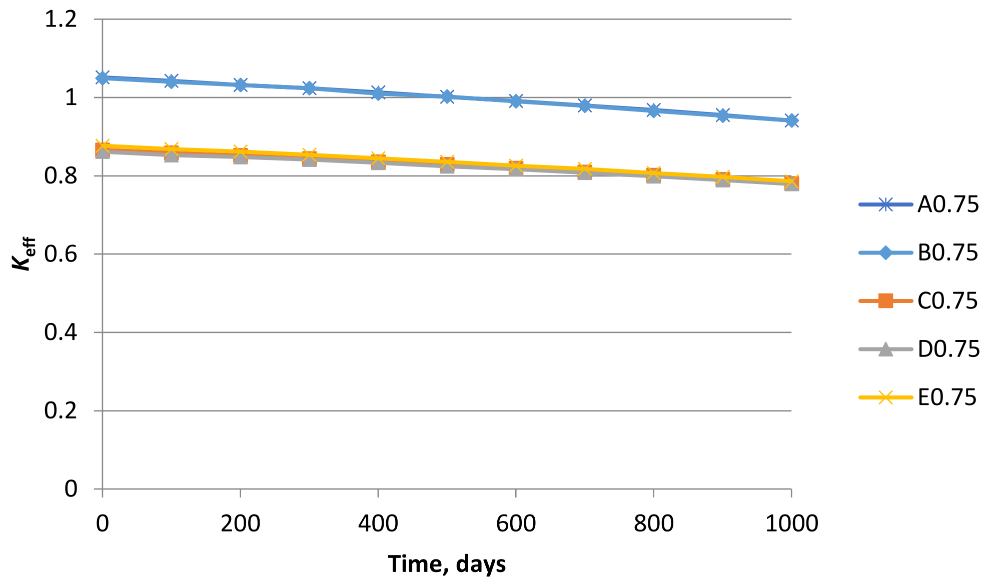


Figure 4.17: k_{eff} of 750 kW power

In Figure 4.17, it shows that the configuration A0.75 and B0.75 have the highest values of k_{eff} until at the middle of the cycle before dropping down to subcritical. As for C0.75, D0.75 and E0.75, the slope of the plots is quite similar and the values of the k_{eff} are under 1.000 from BOC until EOC. This might be due to the distribution of neutron flux that prevents the successful fission of U-$ZrH_{1.6}$ fuels.

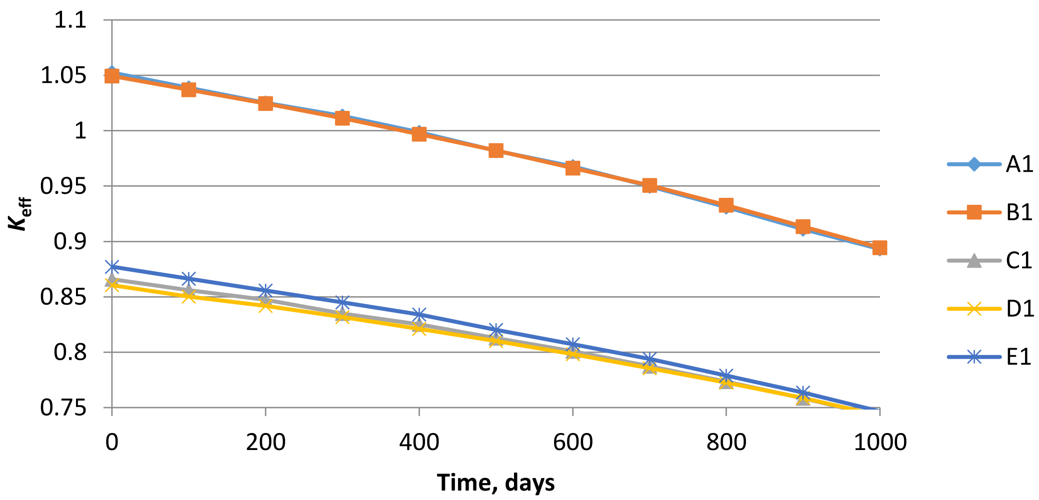


Figure 4.18: k_{eff} of 1 MW power

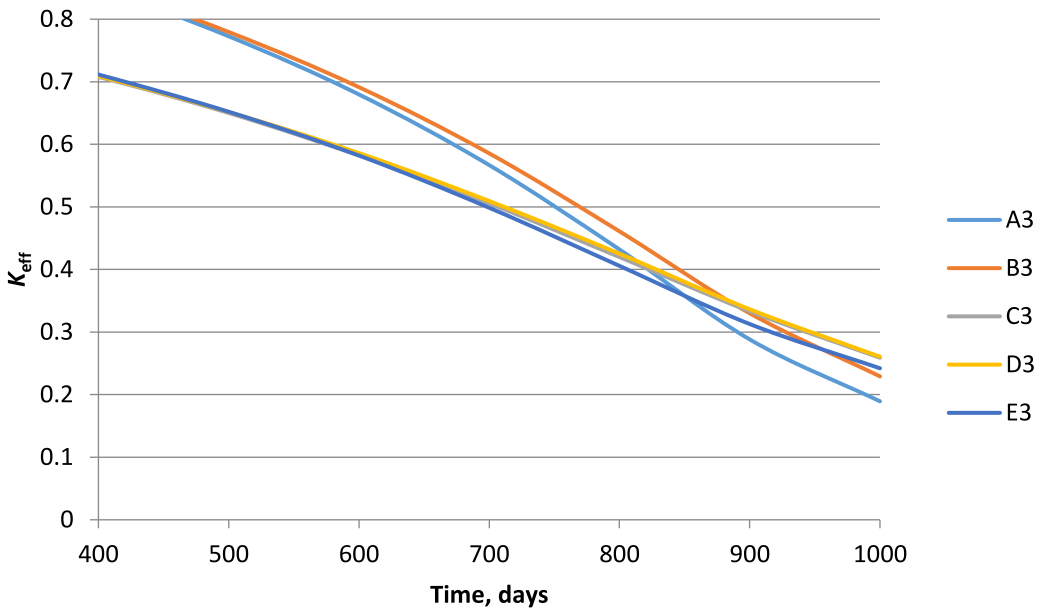


Figure 4.19: k_{eff} of 3 MW power

From Figure 4.19 above, it shows that C3, D3 and E3 lines are overlapping each other. Although the values of k_{eff} for all configurations are below than 1.000, it shows that at the end of the cycle, there is an effect of uranium-233 taking place in the core. The graph shows that the k_{eff} values of C3, D3 and E3 remain steady at the time of 800 days instead of going down like A3 and B3 lines. The value of k_{eff} also due to the higher power of the reactor and the thermal flux is low at the BOC.

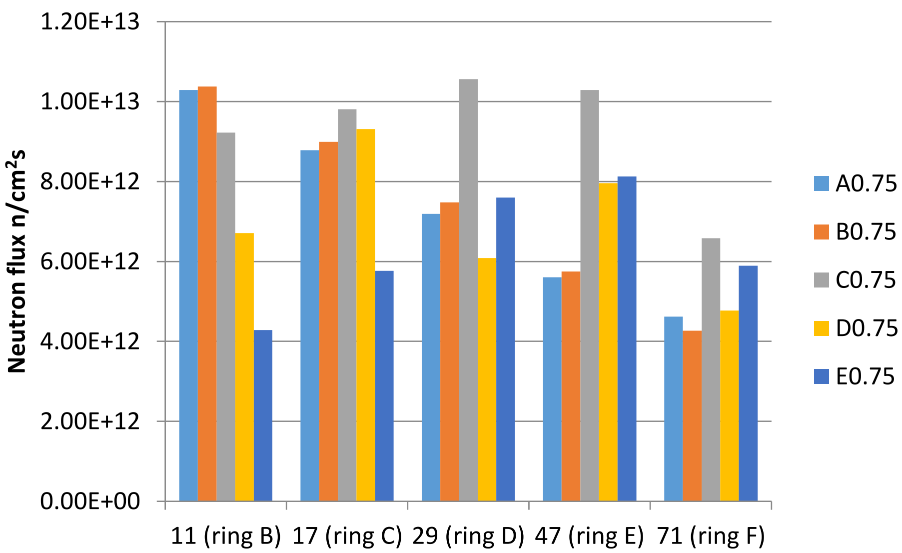


Figure 4.20: Thermal neutron flux 0.75 MW power

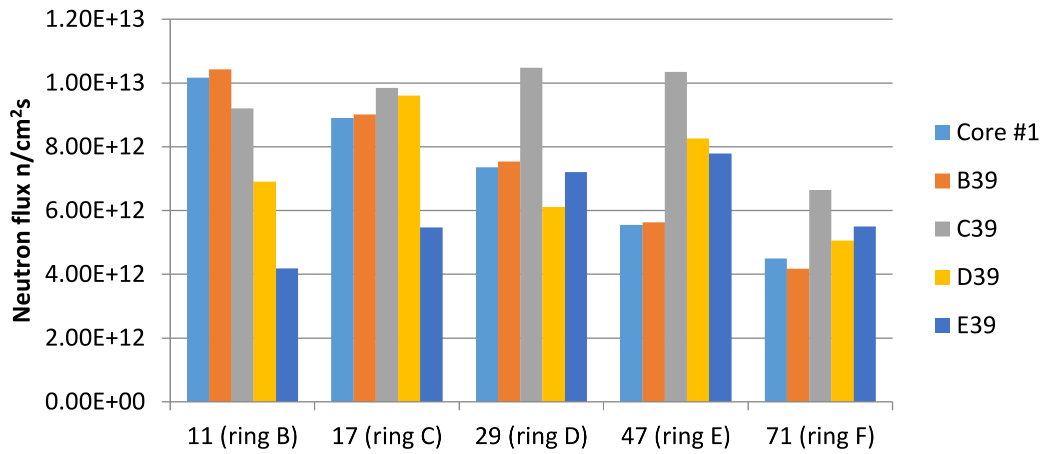


Figure 4.21: Thermal neutron flux 1 MW power

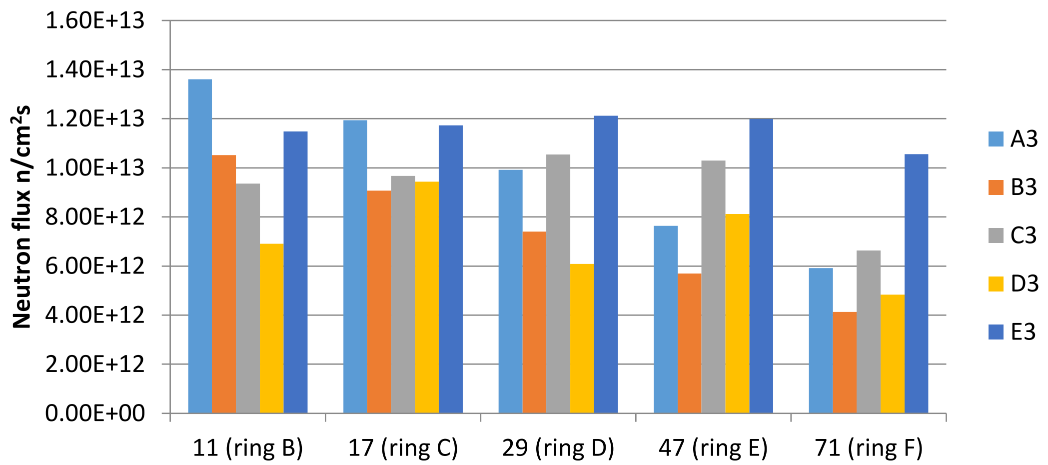


Figure 4.22: Thermal neutron flux 3 MW power

Based on three graphs of thermal neutron flux above, the flux patterns are almost the same. For configurations A and B, thermal flux is the highest at the center of the core. The flux decreases to the outer side of the core.

On the other hand, thermal flux for configuration C is the highest at the middle part of the core (ring D). The value for neutron flux is quite the same from the center core to the outer part of the core. Next, configuration D has an irregular pattern for all part of the graphs. Lastly, configuration E has the flux peak value at ring E at 0.75 MW and 1 MW power. Interestingly, the flux for 3 MW for configuration E, the distribution value of the flux is average from the center to the outer part of the core. It shows that the value of neutron flux for the power 0.75 MW and 1 MW are mostly under $1x10^{13}$ n/cm^{2}s while for 3 MW power, the value of neutron flux mostly above $1x10^{13}$ n/cm^{2}s and the highest value achieved is $1.4x10^{13}$ n/cm^{2}s.

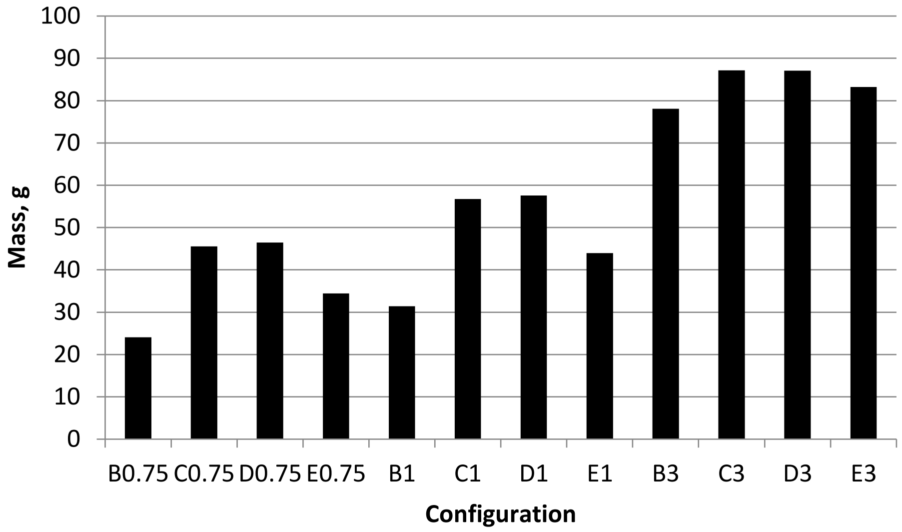


Figure 4.23: Uranium-233 buildup at EOC

Figure 4.23 above shows that the mass of uranium-233 at the end of the cycle. The mass of uranium-233 increases when the power of the reactor increases. The highest reactor power that has been simulated is 3 MW that has the highest mass of uranium-233, which undergoes transmutation process.

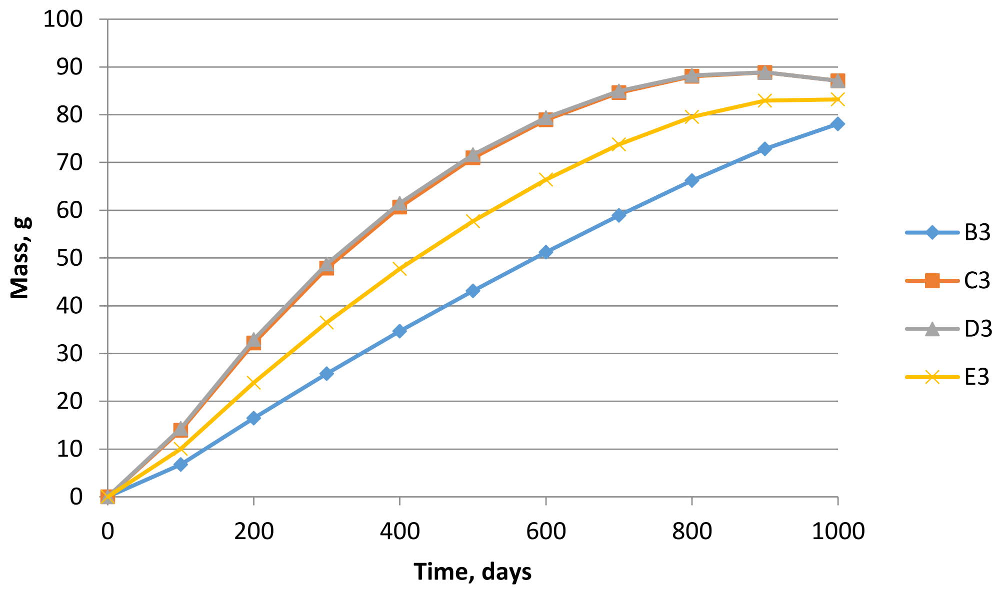


Figure 4.24: The buildup of uranium-233 at 3 MW power

Figure 4.24 above is the buildup process of uranium-233 at the power of 3 MW from 0 to 1000 days simulation. Based on the graph, the B3 configuration shows that the buildup of uranium-233 is increasing at the slowest pace in the graph. Next, configuration E3 has a higher pace of buildup uranium-233 mass with the increasing mass from the beginning of the cycle and going plateau at the end of the cycle. Lastly, configuration C3 and D3 have the same pattern, and both share the highest value in the graph. Notice that on the 900th day, the mass of uranium-233 decreases. This shows that there might be a tiny amount of uranium-233 that was used in the core used for fission reaction.

4.2.3 Fuel Arrangement versus Type of Thorium Fuel

For the last part, the changing variable is the type of thorium fuel use. Three types of thorium fuels have been studied in this simulation, which are thorium oxide (ThO_2), thorium zirconium hydride ($Th\text{-}ZrH_{1.6}$) and lastly pure thorium fuel (Th) as show in Table 4.9. The simulation is carried out using 2500 neutrons per second with 550 cycles and the power of the reactor set to 1 MW. The mass of thorium fuel is fixed with 39 rods of fuel. Table 4.10 shows the simulation result for this arrangement.

Table 4.9: Fuel arrangements for three types of thorium fuel.

Configuration	Thorium oxide	Thorium zirconium hydride	Pure thorium
A	n/a	n/a	n/a
B	Bo	Bz	Bt
C	Co	Cz	Ct
D	Do	Dz	Dt
E	Eo	Ez	Et

Table 4.10: Simulation results for all fuel arrangements with three different thorium fuels.

Configuration	k_{eff}			Buildup uranium-233 at the EOC (g)	Standard Deviation
	Beginning of cycle (BOC)	Lifecycle (days)	Slope		
Bo	1.05992	329	-0.00015	94	0.0034
Co	0.86158	-	-0.00009	173.2	0.0034
Do	0.86798	-	-0.00009	171.8	0.0035
Eo	0.89097	-	-0.00011	133.5	0.0035
Bz	1.04942	276.5	-0.00015	31.4	0.0033
Cz	0.86591	-	-0.00012	56.74	0.0033
Dz	0.86051	-	-0.00012	57.62	0.0034
Ez	0.87721	-	-0.00013	43.96	0.0035
Bt	1.03404	399	-0.00015	164.7	0.0034
Ct	0.79382	-	-0.00007	334.9	0.0035
Dt	0.80739	-	-0.00007	324.3	0.0032
Et	0.86077	-	-0.00011	233.6	0.0033

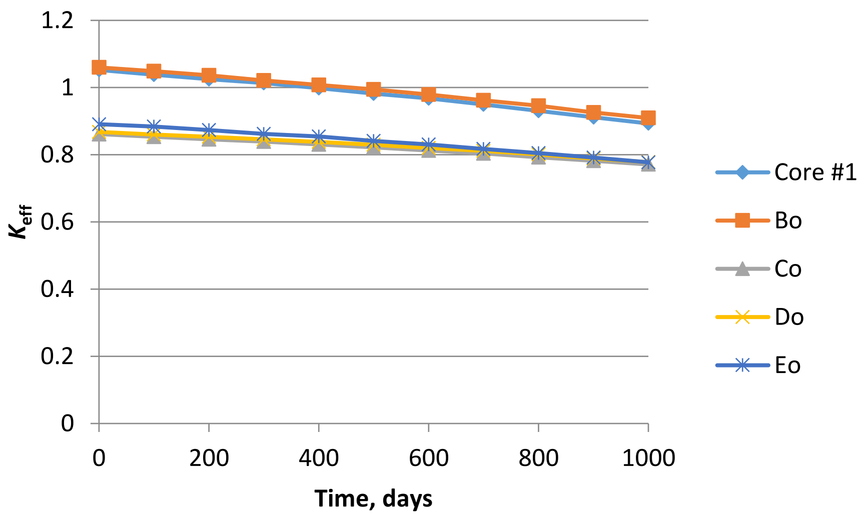


Figure 4.25: k_{eff} of ThO_2 fuel

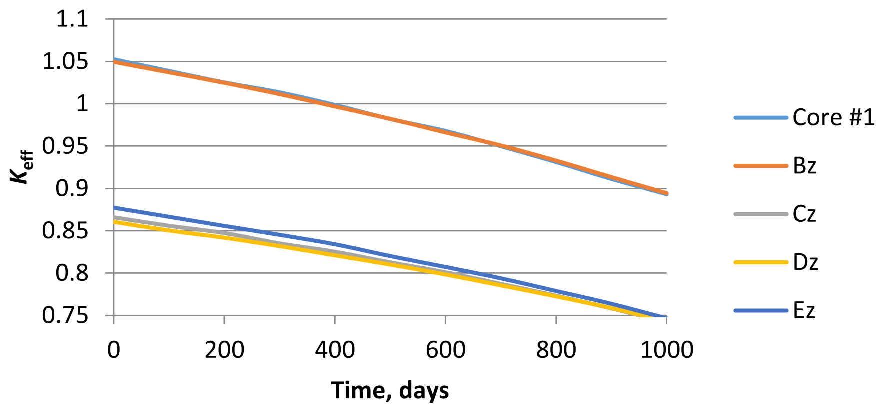


Figure 4.26: k_{eff} of Th-$ZrH_{1.6}$ fuel

From Figures 4.25 and 4.26, Bz and Bo have the same pattern, which is almost similar to core #1. The values for both configurations are almost the same and have the same slope value, which is -0.00015. The differences between the two figures above are the value of the slope. Based on Table 4.10, the slope for configuration ThO_2 are between -0.00009 to -0.00015 while the slope for configuration Th-$ZrH_{1.6}$ is between -0.00012 to -0.00015. The value of the slope shows that the steeper the slope, the faster the time taken for the value of k_{eff} to decrease. Both of the core have same configuration which are seed-blanket configuration. The arrangement of uranium at the centre of the core give the best result as the neutron flux stable at the centre toward outermost of the core. Thus, the keff is higher compare with other configuration.

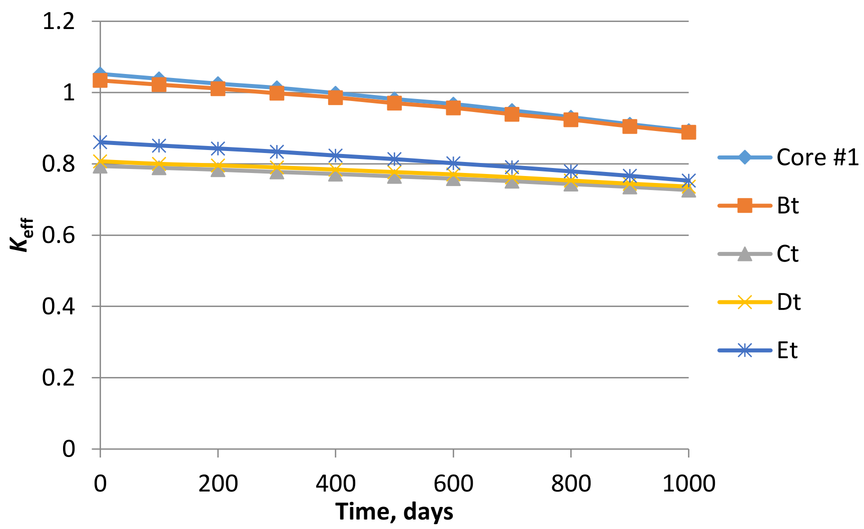


Figure 4.27: k_{eff} of Th fuel

As for Figure 4.27, it shows the same pattern with the configuration of ThO_2 fuel. The slope for configuration that contains pure thorium fuel is between -0.00007 to -0.00015.

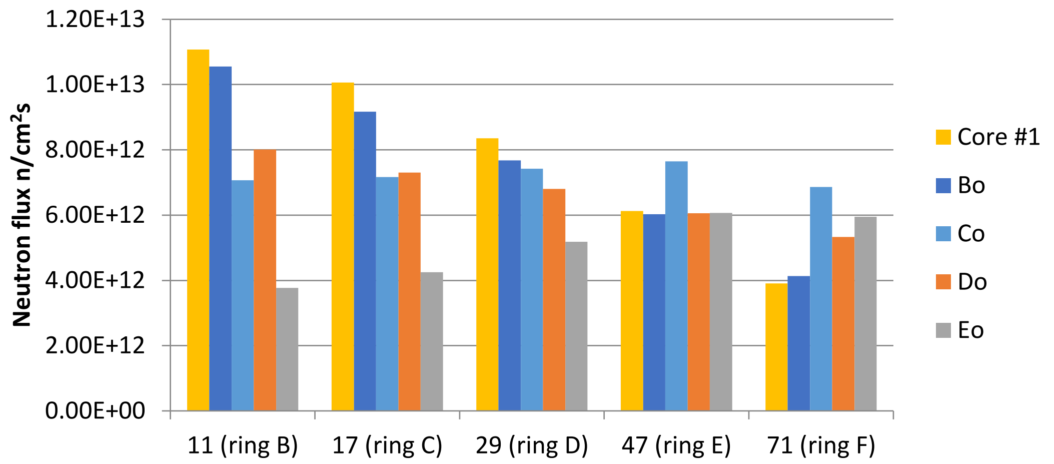


Figure 4.28: Thermal neutron flux ThO_2 fuel

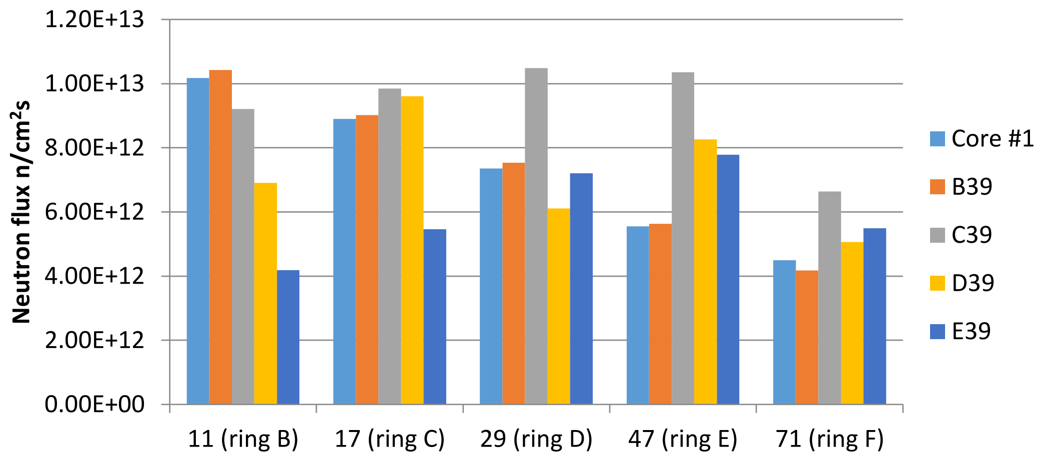


Figure 4.29: Thermal neutron flux Th-$ZrH_{1.6}$ fuel

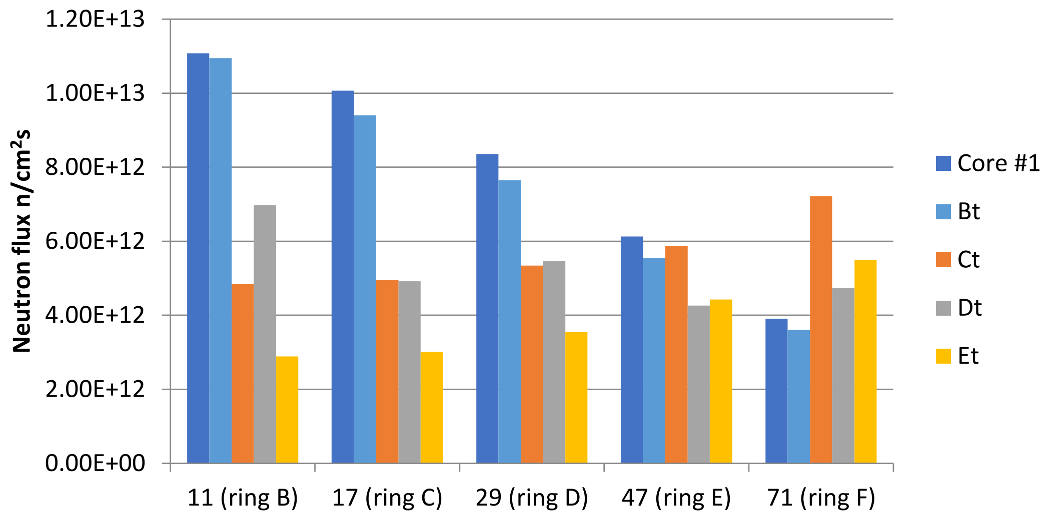


Figure 4.30: Thermal neutron flux Th fuel

Based on Figure 4.28 to Figure 4.30, the thermal flux pattern for each graph is different. For ThO_2 fuel, configurations Bo and Do have the same pattern. The flux is the highest at the center of the core, and later it decreases toward the outermost part of the core. Whereas for configuration Co, the flux is constant at all core rings, beginning from ring B to ring E, before it slightly drops at ring F. Next, configuration F has increasing flux from the center of the core to ring E, and the flux remains constant when reaching ring F.

As for pure thorium fuel, configuration Bt has a decreasing pattern from center to outer part of the core, while configuration Ct and Et have an increasing pattern from center to the outer part of the core. Lastly, configuration Dt has an irregular pattern. The arrangement of fuel rods give different result for neutron flux. The result shows that seed blanket configuration give the best pattern for neutron flux as it is higher at the centre of the core and become lower at the outermost part of the core. The position of uranium fuel at the centre of the core provides neutron for thorium fuel.

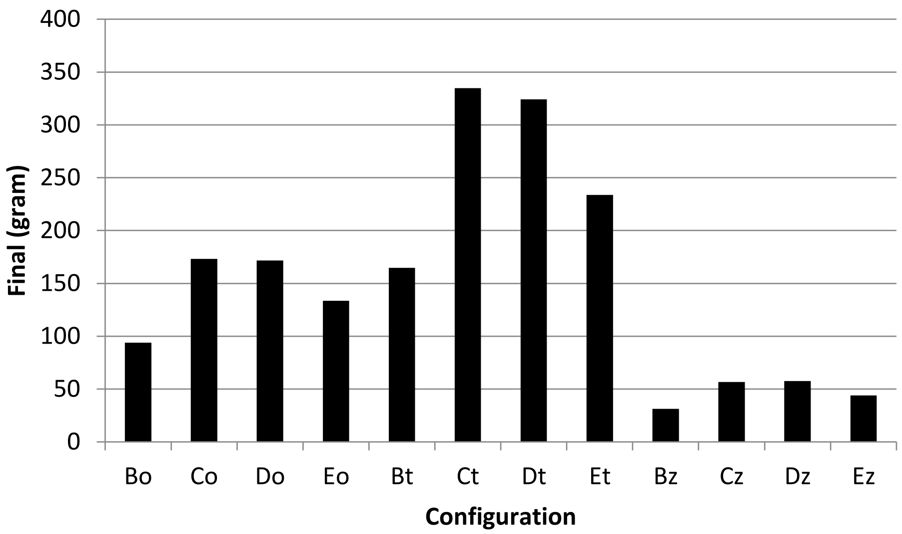


Figure 4.31: Production of uranium-233 for different types of thorium fuel (EOC)

Based on Figure 4.31 above, configuration Ct and Dt have the highest production of uranium-233, which are 334.9 gram and 324.3 gram, respectively. Three of the pure thorium fuel configurations have the highest buildup of uranium-233, followed by ThO_2 fuel configurations and Th-ZrH_{16} fuel configurations. This might be due to the ratio of different elements contain in the fuel with thorium element. Pure thorium configurations produce the highest mass of uranium-233 because the composition of thorium is the highest in the fuel compare with ThO_2 and Th-$ZrH_{1.6}$.

The simulation results show that criticalities, k_{eff}, for configurations C, D and E are very similar in which they are in a subcritical state at the beginning of the cycle. Next, the lifecycle calculation is only available for configurations A and B only. This is because the lifecycle can only be calculated from the k_{eff} at BOC to the critical state of the reactor, which is 1. Hence for configurations C, D and E the lifecycle cannot be calculated because of the sub criticality.

The thermal flux distribution for all configurations shows that neutron flux value at BOC is the same as the real value of RTP core. The pattern of thermal flux affected the value of k_{eff} in each configuration.

Lastly, the highest buildup uranium-233 mass is in the configuration that consists of pure thorium fuel. This is because the concentration of thorium is the highest among all thorium fuel tested.

There are several types of core configuration that have been simulated in chapter 4. The first configuration is core #1 which is designed similar to the original core of RTP. It is simulated to compare the value of k_{eff} with the original core. It is shown that k_{eff} value obtained from configuration core #1 is 1.05139 while the original core of RTP is 1.05677 [14]. Using the value obtained from the simulation, the calculated criticality difference is about 484 PCM, which can be considered acceptable.

Next, thorium is added to core #1 to determine the effects of thorium fuels in the reactor core. There are three types of configuration in this batch with each type consists of 10 different variations. The first one is core 01 which has core 01A, core 01B, core 01C, core 0D, core 01E, core 01F, core 01G, core 01H, core 01I and core 01J. Thorium fuels are added by two rods in core 01A and added two rods gradually until the maximum number of rods are 20 rods, which is core 01J. The cores are simulated with 10000 neutrons per second with 550 cycles. The result from the lifecycle analysis shows that by adding thorium fuel to the core, the lifecycle of the core decreases.

The second core is core 02 that has core 02A until core 02J, totaling up together to 10 cores. Core 02 consists of substitution of fuel rods in the core. Beginning from core 02A, 2 fuel rods from U-$ZrH_{1.6}$ are replaced by 2 thorium fuel rods. The result shows that the lifecycle time for each core decreasing in time from core 02A until core 02J. This is because the values of k_{eff} are also decreasing for each core due to the number of fissile fuels in the core decreases. Lastly, the third core which is labeled as core 03 is the core that has been arranged to the structure of a seed blanket unit core. The uranium fuels that act as a seed are arranged together at the centre of the core while the thorium fuels that act as a blanket are placed at the outermost ring of the core. Study shows that the values obtained from the lifecycle analysis are in an uncertain pattern.

Based on the results that have been obtained from previous batch, five different arrangements of core have been designed to determine the best arrangement. The first one that is labelled with alphabet A is the original core structure that maintains the number of uranium fuels and the arrangement of the fuel. The second configuration, B, is the seed blanket configuration. For the third configuration, C, is the checker type of core that has thorium fuel scattered systematically in the core. The fourth core, D, is the alternate ring configuration which thorium rods are arranged within the ring C, E and G of the core. For the last configuration, E, thorium rods are placed at the centre of the core while uranium fuels are placed at the outermost part of the core.

From the five arrangements, three criteria are being manipulated to determine which core is the best configuration. The first one is the mass of thorium fuel. The cores are tested with three type of thorium mass which are 2 rods, 20 rods and 39 rods. From the results obtained, all configurations B have the positive result and core-B2 has the highest lifecycle with 291 days. Only configurations B are supercritical while the remaining cores do not show values for the lifecycle. The thermal fluxes for all core are in the range of $4x10^{12}$ n/cm^{2}s to $1.07x10^{13}$ n/cm^{2}s which are not far from the real flux of RTP which is $8.7x10^{12}$ n/cm^{2}s [13]. As for the uranium-233 buildup, the highest value the achieved at the end of cycle is 57.62 gram of uranium-233 by core-D39.

For the next criteria is the power the reactor. All five arrangements are tested with different power levels which are 0.75 kW, 1 MW and 3 MW. From the obtained results, only the lifecycle of configurations A and B can be determined as the other cores are mainly subcritical. The highest lifecycle that has been recorded is from core-A0.75 with 575 days. As for uranium-233 buildup, configurations that are simulated with 3 MW show the highest mass of uranium-23 with core-C3 has the highest uranium-233 mass with 87.13 gram. The thermal fluxes for all configurations are in the range of $4.28x10^{12}$ to $1.36x10^{13}$ n/cm^{2}s.

The last part of simulation is the type of thorium fuel. There are three types of thorium fuels that have been used in the simulation, which are $Th\text{-}ZrH_{1.6}$, ThO_2 and Th. The result from the lifecycle analysis shows that configurations B give the acceptable result lifecycle among all the configurations with the highest value can be obtained from core-Bt (399 days). Thermal fluxes are found to be in the range of 2.89×10^{12} to 1.11×10^{13} n/cm^2s. Whereas, the buildup uranium-233 analysis result shows that the highest uranium mass produced among the three fuels comes from Th fuel. Core-Ct has the highest uranium-233 mass with 334.9 gram. Based on the result obtained, in order to introduce thorium fuel in the Malaysia Nuclear Agency's RTP, the suitable configuration that can be implemented is the seed-blanket unit configuration as it gives a similar result with the original core of RTP.

4.3 Limitation

Based on the results that have been obtained, only several configurations give the positive lifecycle values. The simulation result shows that arrangement B, which is the seed-blanket configuration, has the best result for the lifecycle of the core while the other configurations show undesired lifecycle. On the contrary, the buildup uranium-233 analysis shows a favorable outcome with configurations C and D as they offer higher uranium-233 mass production. The thermal fluxes of all configurations give relatively similar readings with the real value of RTP flux.

There are few limitations and assumptions made when carrying out the work. One of them is that we assume the power can be increased up to 1 MW and 3 MW. The actual RTP reactor actually runs with a limited amount of power. The highest power that can be achieved is 1 MW while the operational power is 0.75 MW power.

Another limitation is that this simulation assumes a continuous reactor operation. In reality, the RTP reactor only operates for several hours in a week. Hence, our simulation might have neglected other reactions that might have happened during the non-operating hours of the actual research reactor.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

The result of the study shows that the simulation for thorium in TRIGA PUSPATI Reactor can be done successfully. The research are based on three objectives which are, to performing core computational analysis simulation using MCNPX code on PUSPATI TRIGA Reactor, to investigate the neutron multiplication factor, flux distribution, uranium-233 buildup and fuel cycle length of different types of core configurations with the addition of thorium fuels and to identify the configurations with the addition of thorium that would be suitable for PUSPATI TRIGA Reactor (RTP) operation. For the first objective, the computational analysis simulation for MCNPX have been done by following the real design of core#1 for PUSPATI TRIGA Reactor Nuklear Malaysia. The simulation was performed with a desktop computer that run for at least 9 hours for a core. Design of the core as for the second objective, neutron multiplication factor, flux distribution, uranium-233 buildup and fuel cycle length have been calculated from the simulation of MCNPX with the addition of thorium fuel in the reactor core. It shows that the value of multiplication factor for seed-blanket configuration almost similar with the original configuration of RTP. For the last part of the objective is to identify the suitable configuration for RTP which is the core with seed blanket configuration that have the same pattern trend with the original configuration.

5.2 Recommendation and Future Work

As for a recommendation, to get a better and accurate result, the neutron population needs to be increased to reduce error in MCNPX simulation. Nonetheless, by doing so, it indirectly increases the running time of the simulation. Thus, it is also important to consider upgrading the computer’s CPU power to improve the simulation running time.

For future work, one of suggestions that can be considered is to alter the RTP power higher than this project to get a larger amount of uranium-233 buildup in the end of cycle. In this simulation, there is a significant amount of uranium-233 detected at the end of cycle of the core that has a higher power level.

Another suggestion is to introduce a mixed fuel to the core. The fuel can be a mixed fuel of thorium-232 and uranium-233 in a single fuel rod. The fuel can be represented as the amount of uranium-233 produced by thorium-232 from the transmutation process. Besides, this may prevent the loss of neutron from transmutation process of thorium-232 that can lead to unstable flux distribution and to prevent the lower k_{eff} value of the core.

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