Preliminary Core Design for Thorium Based Gas Cooled Reactor

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1. Introduction

Since the first generation of nuclear reactors, the Generation IV reactors are under development nowadays. Within the development of nuclear reactors, engineers made a lot of attempts to increase the efficiency of the energies to generate electricity, and to decrease the amount of high-level radioactive waste from the nuclear reactors.[1] Due to these reasons, new type of nuclear fuels and reactors were required to achieve long fuel cycles and less high-level radioactive wastes, for these reasons the thorium (Th_{232}) is proposed.

In this paper, purposed to applicate Th_{232} fuel to MAGNOX reactor design, which is designed with gas coolants. The reference model was decided to utilize Calder Hall reactor core design, because it is the earlier gas cooled reactor design in the second generation of nuclear reactor. The main purpose of this paper is to build long life thermal reactor using thorium, and make thorium fueled fast reactor which does not change the geometry a lot from the reference model of core design. The core design was performed with MCNP 6.2, and visualized with Visual Editor.[2],[3]

2. Conditions

The reference model of thermal reactor core is earlier British MAGNOX reactor design Calder Hall reactor. The reason of decision that had chosen the reference model as Calder Hall reactor, is that the core design is much more simple than other gas-cooled reactors. The reference model is shown as following figure. Thermal power and specific parameters of the reactor had been modified as following table.

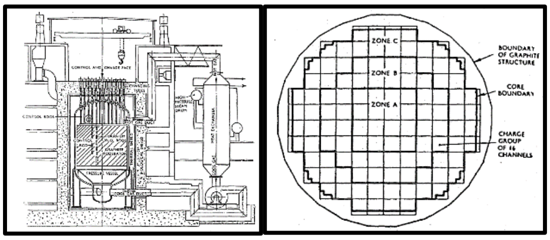

Figure 1. The Calder Hall Reactor Model

Table 1. Design parameters of thermal reactor

Design Parameters	Values
Thermal Power	6.25 MWth
Fuel Material	(^{233}U+Th)Al
Clad Material	Mg+Al
Coolant Material	CO_2
Reflector Material	Graphite
Core Diameter	860 cm
Core Height	735.99 cm

As shown above in Table 1, the metal fuel which is the alloy of U_{233}, Th_{232} and Al is utilized in this reactor. The coolant and reflector material of the reactor will be using CO_2 and graphite as Calder Hall reactor.

The basic reactor design was done; however, the criticality of the reactor will be fluctuated within the enrichment of U_{233}. The enriched uranium-233 had been assumed that it is obtained by THOREX process.[4] Thus, to optimize the criticality of the reactor, prepared 1 wt%, 1.5 wt%, 2 wt%, 3 wt%, 4 wt%, 5 wt% enrichment of U_{233} in the fuel material. Then, the calculation will be performed with optimized fuel material. On the other hand, for the fast reactor, the optimization will be proceeded with enrichment of 20 %, and compared the blanket materials, fuel pitch size, and fuel rod radius.

Table 2. Criticality Results with Various Fuel Compositions

^{233}U Enrichment	keff	std
1.0 wt%	0.9107	0.0056
1.5 wt%	1.135	0.0088
2.0 wt%	1.2594	0.0089
3.0 wt%	1.4476	0.0059
4.0 wt%	1.5404	0.0080
5.0 wt%	1.6564	0.0084

The criticality results had shown as Table 2 with various compositions of fuel, the enrichment of 1.5 wt% and 2.0 wt% had shown enough criticality when it is loaded. However, in order to decide only one fuel composition between these fuel compositions, it is required to compare the criticality result when the control rod (CR) is loaded in the reactor. The material of boron carbide (B4C) had been utilized for control rod to compare the criticality of the fuel compositions.

Table 3. Criticality Results with Control Rods

Conditions	keff	std
1.5 wt% No CR	1.135	0.0088
1.5 wt% CR	0.945	0.012
2.0 wt% No CR	1.2594	0.0089
2.0 wt% CR	1.0652	0.0079

The criticality of the reactor has to show sub-critical when the control rods are inserted in the reactor. As shown in Table 3, the results had shown that the fuel composition which enriched with 1.5 wt% of ^{233}U is safer to be utilized in this reactor. The depletion calculation of this reactor will be proceeded in next section. The final quarter core had been designed with the optimized parameters, and it is visualized with MCNP code and Visual Editor as following figure.

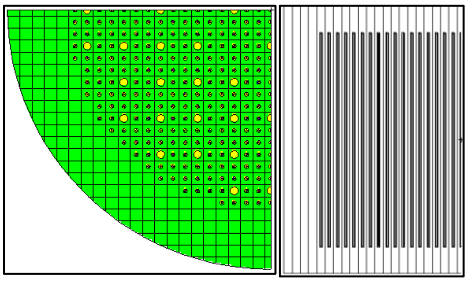

Figure 2. Quarter core (Left) and the axial core design (Right) of thermal reactor

For the fast reactor, the various of the conditions were considered, and the core design of the fast reactor is proposed as Table 4. For this reactor, analysis was proceeded with enrichment of 20 % with U_{233} / Th fuels, and it had been found that the criticality is showing under critical until pitch size of 5, thus, proper pitch size could be 4 cm. If the pitch size is 4 cm, the fuel is needed to be enriched lower than 20%. On the other hand, the pitch size, core height, and core diameter were also needed to be decreased. This changed diameter was calculated with the ratio from the Calder Hall reactor. Finally, it is also required to consider the blanket material which is able to lengthen the life of the reactor. In this paper, in order to reduce the long-lived minor actinides, it is decided to utilize thorium material for the blanket material. The blanket material is assumed to be the thickness of 20 cm in the fast reactor due to maintain enough fission chain reaction. Thus, all modified reactor design parameters are as follow.

Table 4. Design Parameters of Fast Reactor

Design Parameters	Values
Thermal Power	6.25 MWth
Fuel Material	(^{233}U+Th)Al
Clad Material	Mg+Al
Coolant Material	He
Blanket Material	Th-232
Fuel Pitch	4 cm
^{233}U Enrichment	20 wt%
Core Diameter	212 cm
Core Height	147.198 cm

With above condition, the quarter core design had been visualized with MCNP and Visual Editor as thermal reactor. The fast reactor core design had shown as following figure.

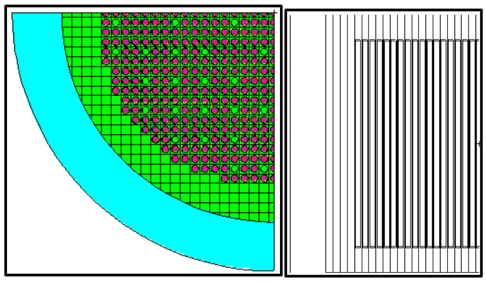

Figure 3. Quarter core (Left) and the axial core design (Right) of fast reactor

As shown in figure 1 and 2, both reactors are showing similar designs without the blanket material at the boundary of the fast reactor. However, with those reactors, it is required to figure out the life of the reactor which could sustain the criticality of the reactor in critical state. In next section, the spectrum of the reactor will be calculated with MCNP code to prove that the designed reactor is belongs to thermal reactor or the fast reactor.

3. Analysis

With the optimized design of the reactor, it is required to prove the reactor occur fission reaction in fast neutrons or thermal neutrons by utilize the MCNP code. If the reactor sustains the fission chain reaction with thermal neutrons, which is representative characteristic of thermal reactor, the spectrum of the reactor will show two stand out peaks. On the other hand, if the reactor sustains the fission chain reaction with fast neutrons, which is representative characteristic of fast reactor, the spectrum of the reactor will show only one remarkable peak.[5] Therefore, the calculation of the neutron spectrum had been performed with MCNP code by utilizing F4 tally which is one of the function in MCNP. The results had shown as following figures.

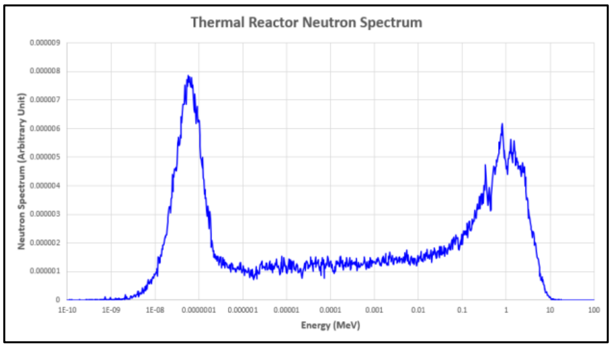

Figure 4. Neutron spectrum of the thermal reactor

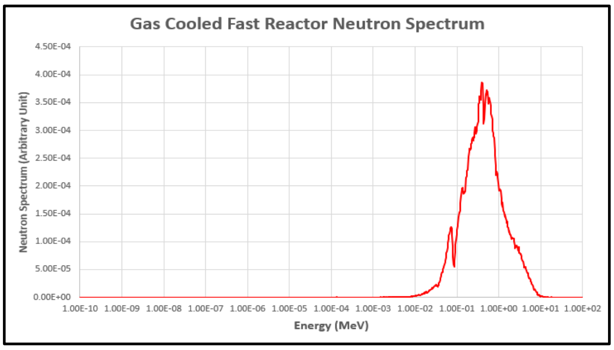

Figure 5. Neutron spectrum of the fast reactor

According to above results, the gas-cooled thermal reactor is showing the two remarkable peaks as mentioned above, and the gas-cooled fast reactor is showing only one remarkable peak which had describe above too.

Finally, the depletion calculation was performed to find out the lifetime of the reactors. The results of depletion calculation are described in next section.

4. Result

The calculation of criticality was performed by utilizing ENDF/B-VII.1 cross section library in MCNP 6.2. For both fast and thermal reactors, calculated in same depletion times, and the result had shown as follow.

Table 5. Criticality of thermal reactors

Burnup (GWd/MTHM)	Thermal Reactor keff	std
0.00E+00	1.10449	0.00039
9.79E-04	1.10395	0.00041
1.08E-02	1.10425	0.00037
4.65E-02	1.10290	0.00036
1.18E-01	1.09995	0.00041
2.25E-01	1.09695	0.00045
1.21E+00	1.08710	0.00044
4.14E+00	1.06429	0.00045
1.00E+01	1.03171	0.00038
1.98E+01	0.99738	0.00045

Table 6. Criticality of fast reactors

Burnup (GWd/MTHM)	Fast Reactor keff	std
0.00E+00	1.14917	0.00165
1.96E-02	1.14972	0.00195
2.15E-01	1.14595	0.00207
9.30E-01	1.14468	0.00171
2.36E+00	1.14214	0.00190
4.51E+00	1.13691	0.00207
2.41E+01	1.09385	0.00186
8.29E+01	0.96409	0.00169
2.00E+02	0.76802	0.00162

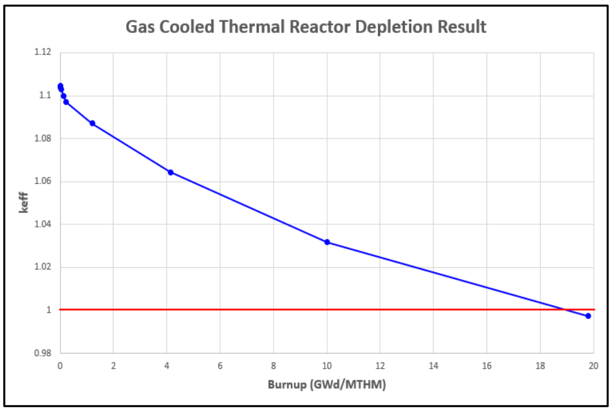

Figure 6. Criticality change of thermal reactor

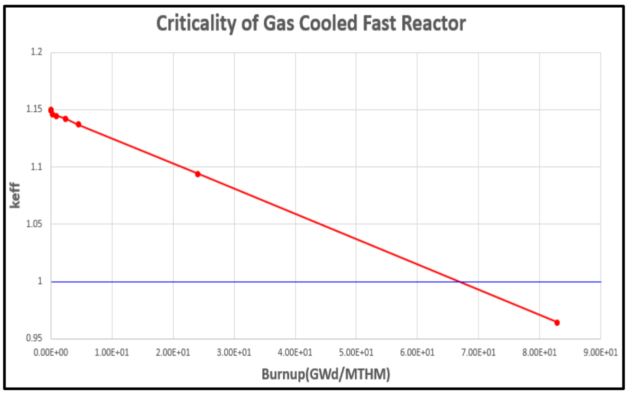

Figure 7. Criticality change of fast reactor

As shown in Table 5 and Figure 5, the reactor is showing critical until 10 GWd/MTHM. In addition, as shown in Table 6 and Figure 6, the reactor is showing critical in burnup of 24.09 GWd/MTHM, but it had shown sub-critical at the burnup of 82.85 GWd/MTHM, which means that the reactor may show critical between the burnup of 25 GWd/MTHM and 70 GWd/MTHM. With the depletion results of the reactor in this paper, it had shown enough probability of thorium fuel in gas-cooled reactor.

5. Conclusion

The analysis of gas cooled reactor is performed with fuel material of thorium. The calculations were performed with MCNP 6.2 code which can calculate out depletion and criticality calculations. The reactors in the past and now were using only enriched uranium. Thus, in this paper, the fuel using thorium which enriched with U_{233} is proposed. The calculation was proceeded from changing the fuel composition from the reference model of Calder Hall reactor, and then the calculation results was shown as Table 6, 7 and Table 5, 6. These results had led the idea of this reactor to fast reactor, and the proposed fast reactor core was designed. The results of fast reactor had shown as figure 6 and table 3. The criticality of fast reactor was high enough, and the result of depletion calculation which had shown in figure 5 and 6 is showing that the criticality of fast reactor is decreasing much less than thermal reactor. These results had shown that the thorium fueled gas cooled reactors have high probability of new generation reactor. For the future work, more calculation will be performed with various conditions of fast reactors, and the validation will be done with other codes.

REFERENCES

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[5] John R. Lamarsh, "Introduction to Nuclear Engineering", 3rd Edition.