A New Conceptual Core Design of Mobile Thorium based Small Modular Reactor for the Medical Applications

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1. Introduction

BNCT is a type of cancer treatment that uses a neutron beam to target tumor cells. The neutron beam is generated by a nuclear reactor, and historically this has been done using large research reactors. However, SMRs have been proposed as a potentially more practical and cost-effective solution for BNCT [1].

Some SMR designs being considered for BNCT include the High-temperature Gas-cooled Reactor (HTGR), the Molten Salt Reactor (MSR), and the Integral Pressurized Water Reactor (iPWR). Each of these designs has unique advantages and challenges for BNCT.

Overall, the development of SMRs for BNCT is still in the early stages, and there are many technical, regulatory, and financial hurdles that will need to be overcome before SMRs can be widely deployed for this application.

As medical and radiochemical technologies advance, the BNCT studies have arrived almost the applicable level. As a possible option, the SMR is considered in this study, and it may be transported to the hospital and dock to the BNCT treatment **(Figure.1)**.

However, there is growing interest in SMRs for a variety of applications, and it is possible that BNCT could be one of the many potential uses for this technology in the future.

2. SMR Design

The reactor unit operates at 30 MW thermal power output. The core contains 13 fuel assemblies in a 17 × 17 type arrays **(Table.1) (Figure.2)**. The fuel pin contains TRU 15%, U233 5% and Th232 80%.

Thorium is safe and produces less radioactive waste than the uranium nuclear cycle. The fission material U_{233} is provided by THOREX process [2]. transuranic elements as fuel enables sustainable and economical energy production. Transuranic elements (TRUs) were released from PWR at 45,000 MWD/MTU burnup, which was followed by a 10-year cooling process and was obtained via the LWR SNF [3] **(Table.2)**.

Once fuel loaded, this core operates long-term soluble boron-free operation without fuel replacement. Operating without boron improves fuel efficiency and safely controls the cycle.

Using (U233+TRU+Th232)O_2 fuel has many reason like abundant availability of thorium, less long-lived radioactive waste compared to conventional fuels like U235 and Pu239, thorium has higher thermal efficiency than U235 and Pu239, which means it can produce more energy per unit of fuel, lower risk of nuclear proliferation and safety. But there are still technical and economic challenges that must be addressed before these fuels can be widely used in nuclear reactors.

The detector was installed in the inner core area to check the minimum condition of the epithermal neutron flux $1 \times 10^9 n/cm^2 sec$ in the air to check if the core is a suitable for BNCT. Graphite was selected inner core reflector among them in consideration of economic feasibility. **Table.3** shows the reactors used in BNCT in the past. BMRR is a medical reactor, and the rest of them are research reactors. [4,5,6,7,8]

Table 1 Assembly parameters

Fuel Composition	(U233+TRU+Th232)O_2
Coolant	H_2O
Reactor vessel	SS316
Active Length	1.2 m
Core Rad.	1.2 m
Rod Pitch	1.26 cm
Rod diameter	0.95 cm
No. of rods	264
Clad type	Zr-4
Thermal Power	30MWth

Table 2 TRU compositions

TRU Nuclides	wt%	TRU Nuclides	wt%
Np-237	1.7152	Am-242	0.2234
Pu-238	3.0176	Am-243	1.1902
Pu-239	50.0963	Cm-242	0.0031
Pu-240	31.9379	Cm-243	0.0103
Pu-241	3.8629	Cm-244	0.7526
Pu-242	3.1988	Cm-245	0.2440
Am-241	3.6076	Cm-246	0.1400

Table 3 Formal BNCT reactor neutron flux

BNCT Reactor (Power)	Thermal neutron flux
BGRR (20MWt)	2.80×10^{12}
BMRR (3MWt)	6.20×10^{9}
MITR (5MWt)	3.60×10^{13}
JRR-3 (10MWt)	2.00×10^{14}
JRR-4 (3.5MWt)	7.00×10^{13}
KURR (5MWt)	1.06×10^{14}

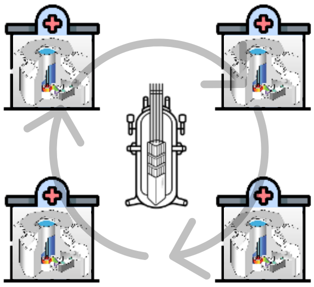

Figure 1 Mobile SMR concept

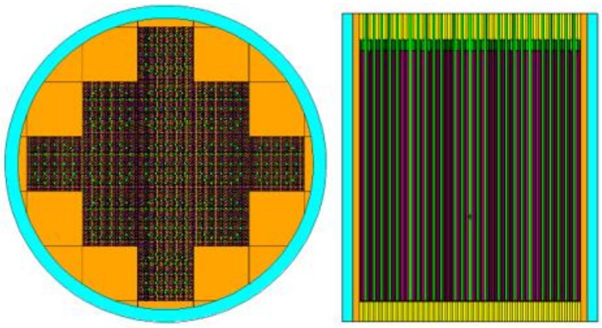

Figure 2 BNCT SMR

3. Methodology

In this paper, the values of (U233+TRU+Th232)O_2 fuel are analyzed. The model was created via the three-dimensional core design of the MCNP6.2 code. The critical calculation of the core was provided by the code.

The criticality (KCODE) calculation was performed using 200 million histories (2×10^8) in 100,000 initial sources, 2,000 active and 200 inactive cycles, 1.0 initial criticality guess and ENDF/B-VII.1 neutron cross-sectional library. The cycle length was measured using the BURN card for the depletion calculation.

The epi-thermal neutron fluence in the phantom is generally limited to $5 \times 10^{12} n/cm^2$. Secondly, neutron beams should not contain fast neutrons and gamma rays that backfire on BNCT as much as possible [9].

Fast neutrons and gamma rays cannot be excluded about neutron beams using nuclear reactors. However, fast neutrons are limited to $1 \times 10^{-11} cGycm^2/n$ or less because they have a fatal effect on skin tissue, Gamma rays are also limited to approximately $1 \times 10^{-11} cGycm^2/n$. Third, it is very important to reduce the neutron beam irradiation time if the directionality of the beam is good.

The epi-thermal neutron flux in the air should be $1 \times 10^9 n/cm^2 sec$ or more for an effective BNCT. The method for a reactor that is currently being used is the most effective [4]. The neutron flux inside the neutron beam was briefly obtained by a simulation.

3. Results

The effective multiplication factor was 1.16246 ± 0.00005, and the subcritical value was maintained at 0.95 when the control rod was inserted. It showed a cycle of at least 12 years.

The moderator and fuel temperature coefficients of reactivity were calculated **(Figure.3)**. For this study, moderator temperature is increased from 293.6K to 600K. As we know, the density of water decreases with increasing the moderator temperature and impact on the neutron absorption by fissile materials.

FTC is calculated for the potential options by increasing the fuel temperature from 293.6K to 600K. If the temperature of fuel is increased, the relative thermal motion of fuel atoms and neutrons which cause an effective broadening of the resonances capture cross-section of fertile nuclides. The reactivity of FTC increased from -6.20 pcm/K to -3.50 pcm/K but remained negative throughout the entire cycle. The reactivity of MTC also decreased from -6.45 pcm/K to -3.56 pcm/K but remained negative throughout the cycle. The uncertainty varies between 1.22E-07 to 1.31E-07.

Figure.4 illustrates that U_{233} tended to increase with the production at Th_{232}, and Pu_{239} was converted to other nuclides as it burned during the cycle.

Figure 3 Safety Parameter (MTC, FTC)

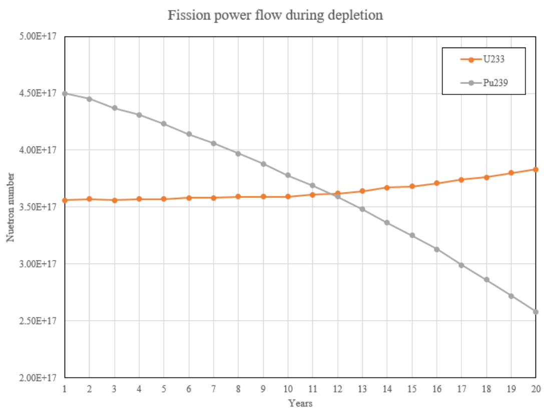

Figure 4 Fission power flow during depletion

Average result of Power Peaking Factor was 1.045. The Power ratio is also homogeneously distributed close to 1 for each assembly. This means that there is no need to adjust the poison material for peaked assembly, but it may be necessary for the initial reactivity control. **(Figure.5)**

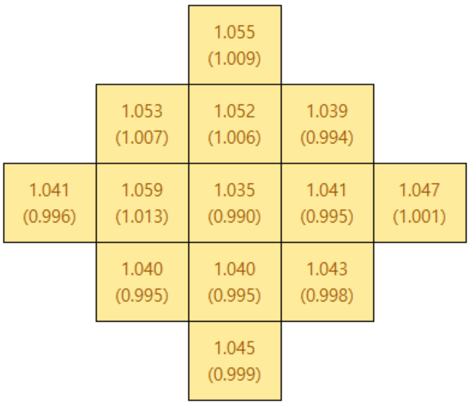

Figure 5 Power Peaking Factor and ratio

The detector was installed in the inner core area to check the minimum condition of the epi-thermal neutron flux $\mathbf{1 \times 10^9} \boldsymbol{n/cm^2sec}$ in the air to check if the core is a suitable for BNCT. The result of epi-thermal neutron flux was $\mathbf{4.62 \times 10^{10}} \boldsymbol{n/cm^2sec}$ **(Table.4)**.

Table 4 Neutron flux result

Neutron flux requirement (n/cm^2sec)	Result (n/cm^2sec)	Neutron flux Limit (n/cm^2sec)
1×10^9	4.62×10^{10}	5×10^{12}

5. Conclusion

The purpose of this paper is to develop the concept of SMR, which can be applied directly to the hospital where a patient is set, because other research reactor's that are also installed in the area cannot be moved, such as large reactors. Detailed modeling and specific calculations were performed using MCNP6.2 code.

The cycle length of the core showed an output that is capable of driving for 12 years. The calculation results of safety parameters from BOC to EOC demonstrated reactor safety. The periodic trends of fission materials U233 and Pu239 were examined. Power Peaking Factor were homogeneously formed and resulted in values close to 1. Epi-thermal neutron flux of $4.62 \times 10^{10} n/cm^2$ in beam was calculated to confirm the performance of the BNCT reactor.

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