A Preliminary Core Design of the Thorium based Epithermal Icebreaker Reactor

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1. Introduction

Russia has been developed its nuclear-icebreaker reactor ship as this nation tries to step up its military, trade and exploration activities in the Arctic. And it is known as the first country to have the largest number of nuclear icebreaker reactor ships, which allow to create a route through the thick of ice in the Arctic[1]. The development of nuclear icebreaker reactor is under progress and there are some plans to make more new ice breaker ships within the next 10~15 years [2]. The ice breaker reactors is designed to be compact and small, thus it is categorized as a small modular reactor(SMR), for instance, the RITM200 of Russia[3].

In this study, a preliminary design of the epithermal neutron spectrum icebreaker reactor ship is proposed based on the combination of ^{232}Th+^{233}U and Zr metal fuel. 19 fuel rods are arranged in one hexagonal fuel assembly. Abundant thorium has lots of merits when the neutron spectrum is shifted to epithermal region from the fast neutron spectrum. In order to achieve more epithermal neutron spectrum, some hydrogen is added in the metal fuel rod. Some sensitivity studies for hydrogen content are also carried out in this paper by using MCNP code[4]. Depletion analysis is also performed to estimate the cycle length and neutron flux distribution are provide, too.

2. Nuclear Design of Icebreaker Reactor

2.1 Basic Design Parameters

Fuel rod and fuel assembly are in the shape of a hexagonal. The configuration of fuel rod and shape of fuel assembly are based on the existing icebreaker [3]. Fuel rod is consisted of thorium and uranium metal with zirconium alloy. Hydrogen is added as an impurity level to obtain soft neutron spectrum. The weight fraction composition of thorium and uranium metal fuel is around 90 wt% and that of zirconium is 10 wt%. The uranium is fully composed of U-233 in order to ensure non-proliferation resistance property of thorium cycle.

The configuration of fuel assembly for the icebreaker reactor is depicted in Fig 1. The reactor core is composed of 439 fuel assemblies (FA) and 19 fuel rods consist in one FA as shown in Fig. 2. Nuclear design parameters are described in the Table 1. The proposed icebreaker nuclear reactor provides 100 MWth which is equivalent about 30 MWe. The suggesting coolant is a lead-bismuth which has a better water-resistance property than liquid sodium coolant.

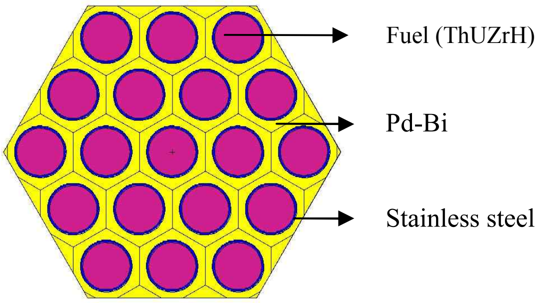


Fig 1. Cross-section view of a hexagonal fuel assembly.

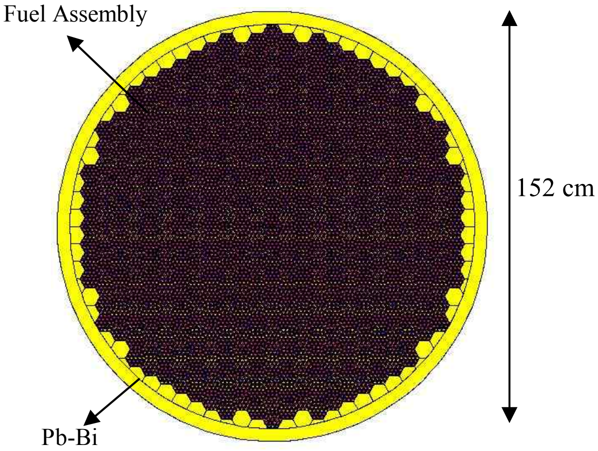


Fig 2. Full size horizontal view of the icebreaker reactor

Table 1. Nuclear design parameters of the icebreaker reactor ship

Nuclear Design	*Characteristic*
Reactor Power	100 MWth
Fuel type/FA array	ThUZrH / Hexagonal
# of FRs per FA	19 FRs
# of FAs in core	439 FAs
Coolant material	Pb-Bi
Core diameter	152 cm

2.2 Analysis Condition

MCNP6.1 code is used to core design with depletion calculation, which provides an accurate solutions with three-dimensional design without lots of approximations.[4] In order to determine k_{eff} of the core, the KCODE card of MCNP6.1 code is used with ENDF/B-VII.1 cross-section libraries. For the calculation, 10,000 neutron histories are used to run for 250 active cycles with inactive 50 cycles.

3. Result and discussion

In this section, some analysis results of thorium based icebreaker reactor are provided by using the MCNP6.1 including neutron spectrum, power distribution, and reactivity change as burnup change.

3.1 Hydrogen Content and Neutron Spectrum

Hydrogen is added in the ThUZr fuel so as to enhance the epithermal neutron spectrum. Some sensitivity analyses are carried out by changing the content of hydrogen as shown in Table 2. The effective of multiplication factor, k-eff increases steeply when the content of hydrogen increases from 0.1 wt% to 0.7 wt%. The neutron spectrum of ThUZrH is also shown in the Fig 3. It is found that the spectrum is slightly shifted to the left region, which means that epithermal neutron spectrum is enhanced by increasing neutron contents. But too skewed to the epithermal region, it is not good to provide neutron economy due to increased capture.

Table 2. k-eff change with various hydrogen contents of the icebreaker fuel

Case Study	*Composition of Fuel*	*k-eff*
Base Case	ThU 90 % and ZrH 10% (H 0.1%)	1.23505
Case 10	ThU 90 % and ZrH 10% (H 0.2%)	1.34155
Case 11	ThU 90 % and ZrH 10% (H 0.3%)	1.42118
Case 12	ThU 90 % and ZrH 10% (H 0.4%)	1.48058
Case 13	ThU 90 % and ZrH 10% (H 0.5%)	1.52948
Case 14	ThU 90 % and ZrH 10% (H 0.6%)	1.56559
Case 15	ThU 90 % and ZrH 10% (H 0.7%)	1.59724

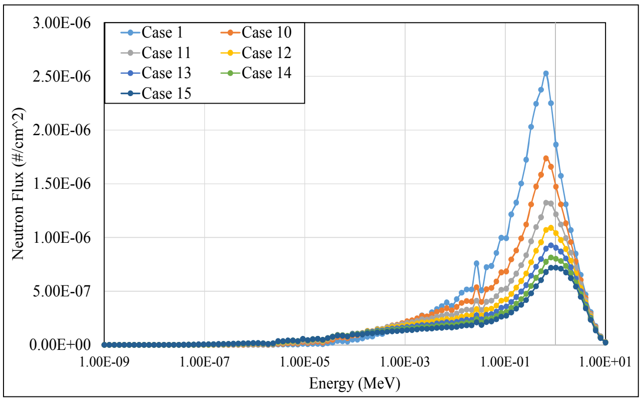


Fig 3. Neutron spectrum of ThUZrH with the variety of hydrogen content.

3.2 Neutron and Power Distribution

Neutron distributions of $ThUZH_{0.01}$ fuel loaded icebreaker reactor are shown in three regions such as thermal, epithermal and fast energy as shown Fig. 4. It depicts that the interaction between neutrons and fuel is occurred at the higher range of neutron energy than that the lower energy.

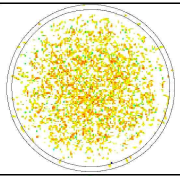
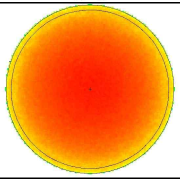
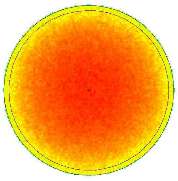
Energy Range	$ThUZrH_{0.01}$
Thermal energy (0 ~ 6.26E-6 MeV)	
Epithermal Energy (6.26E-6 ~ 1MeV)	
Fast Energy (1 ~ 10 MeV)	

Fig. 4. Visualization of Neutron Distribution of $ThUZrH_{0.01}$

3.3 Depletion Analysis

The depletion calculation of nuclear icebreaker reactor is performed by using the BURN card of MCNP6.1 code, which is combined with CIDER depletion module. The cycle length of icebreaker reactors, for instance RITM200, can be operated for 7 years long before refueling[3]. In this study, it is preferable to have longer cycle length rather than that of RITM200 reactor. The depletion calculation of icebreaker reactor ship is displayed in the Fig. 5. The cycle length is approached to be around 48,000 MWD/MTHM, which is corresponding to about 15 years. From the results, there are lots of margins even for the end of cycle.

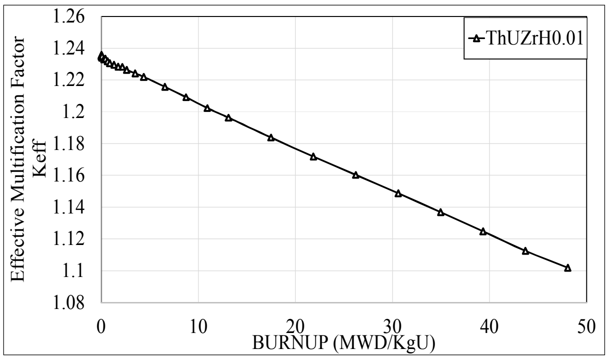


Fig 5. Depletion calculation of nuclear icebreaker reactor ship.

4. Conclusions

The preliminary design of epithermal nuclear-powered icebreaker is presented by using thorium metal fuel by introducing small quantities of hydrogen. From the analysis of neutron spectrum of ThUZrH fuel, neutron distribution can be adjusted by modulating hydrogen content. Additionally, the depletion calculation are carried out and it shows that the possibility of increased fuel cycle length.

The detail analysis will be followed including safety parameter analysis such as MTC, FTC, control rod worth, and safety margin. As a conclusion, the thorium based epithermal icebreaker reactor is very challenging and promising with advanced nuclear core design technology.

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