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A Design Study of Small Space Reactor with High Enriched Uranium Fuel

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1. Introduction

A large number of space probes have been launched to explore space. There have been some plans for deep space exploration but only eight explorations were performed until now because of the problem of power source. Typical space probes mainly use a solar battery, but it's hard to use it, because the energy density is too low to provide sufficient power. Other power sources usable are nuclear energy such as a radioisotope thermoelectric generator (RTG) and a space reactor. A space reactor generates power with the chain fission reaction and is capable of a long life power source. Unlike a solar battery, a space reactor is independent from environment, and can generate larger power than that of RTG. Since a space reactor has these advantages, a space reactor is very promising power source to perform future space explorations which require a large amount of power. A lot of research and development on the space reactor has been performed. The reactor mass and the reactor size are one of the important concerns about a space reactor design. A space reactor should be fabricated as light in weight and small as possible. In the past study, the low enriched uranium fueled space reactor was designed on the basis of the above design requirements [1]. This study was performed in the aim of the reduction of movable part, elimination of liquid cooling, automatic operation. This reactor was designed as a thermal reactor and the fuel was composed of 20 % enriched U-Zr fuel and $ZrH_{1.65}$ moderator was used. The fuel and moderator elements were pin-type one and cladded by Zr-2.5%Nb. Fuel and moderator pins were arranged in triangular array in Be structural material covered by Be reflector. B_4C rods and LEM (Lithium Expansion Module) were adopted to control power. Heat from the core was converted to electricity by heat pipes and thermoelectric conversion elements. The total reactor mass including Be reflector and structural material was 241 kg, and the reactor diameter and height were 45 cm with a B_4C control rod system and heat pipes in the core. The fuel lifetime was 6 years when thermal power is 40 kW. This reactor is small, but it is possible to additionally decrease the mass and size of reactor by changing uranium enrichment. In this study, a space reactor with high enriched uranium is designed in order to explore the possibilities of the further reduction in size and weight, the high power, and the long lifetime.

In this paper, a design study of small space reactor with high enriched uranium fuel is presented. Chapter 2 describes the outline of thermal and nuclear design. In chapter 3, the thermal design such as thermal power, the core temperature, and the number of heat pipes are performed. The nuclear design is surveyed in chapter 4 to aim at designing the small and light reactor which has a long lifetime. The number of control rods which are required to keep critical is also calculated. Particularly, the minimum critical mass and fuel lifetime are important. Finally, chapter 5 summarizes this study.

2. Outline of Core Design

In this chapter, the methods of neutronics and thermal design are mentioned. The demand lifetime of the power sources for deep space explorations has been about 10 years due to highly-developed space missions [2]. In this paper, the core is designed on the basis of following conditions; it has more than 10 years lifetime, the total mass and the core size are smaller than 241 kg and 45 cm, and it has the maximum thermal power which is decided by the thermal design. In many of the past designed space reactors, heat generated by fission in the core is converted to electrical power after transported by coolant or heat pipes to convertor, and the rest of heat is released into space by radiator panels. In this paper, just like these space reactors [2], heat pipes which are inserted into the core, thermoelectric power generation, and radiator panels which directly connect to heat pipes are used. The structure material of heat pipes, working fluid, and material of capillary structure are Mo, Li, and stainless steel respectively. The outer and inner diameter of heat pipes are 18 and 17 mm. The conversion efficiency of the thermoelectric power generation is assumed 8 % [2]. In the reactor used in this paper, high enriched uranium fuel is used to compose fast reactor for the reduction of the reactor size and mass. 90% enriched UC_2 is adopted as the fuel material in order to have a high thermal conductivity and high melting point. Stainless steel is used as the cladding material. The diameter of fuel pin is 7 mm. The fuel is enclosed into a 0.4 mm thick cladding, and arranged in triangular array in BeO structural material. The structural material is covered by BeO reflector. BeO has a low neutron absorbing capability, and high thermal conductivity, and high melting point. The core is cylinder core with the height equal to the diameter. B_4C rods are introduced to control the criticality of the core, B_4C pellet is covered by the same cladding as a fuel cladding. Heat pipes are placed in the reflector of the core to remove heat from the core.

In thermal design, first, the temperature of the designed core is calculated. It is assumed that the core temperature is the same in the whole core. The core temperature should be lower than the melting points of the structure materials of the core in terms of safety.

Second, the required number of heat pipes is investigated by considering the heat transport performance and thermal power of the reactor.

In nuclear design, minimum critical mass is investigated by changing the size of the core and the thickness of the reflector. In order to design the core which fulfill the demand lifetime, the lifetime of the core with minimum critical mass are also investigated. The number of control rods to keep critical is computed. The calculation about minimum critical mass and the number of control rods is performed using a continuous energy Monte-Carlo code MVP [3], and fuel lifetime is computed with MVP-BURN [4]. All calculations are carried out by using JENDL-3.3 cross-section libraries.

3. Thermal Design

In this chapter, the thermal design is performed based on the design method mentioned above. The thermal power and temperature of the designed core, and the required number of heat pipes are calculated.

3.1 The thermal power and temperature of the core

In this section, the maximum thermal power and temperature of the core are determined. The design should be performed to satisfy the core temperature criteria of the melting point of fuel cladding because its melting point is the lowest of that of the structure materials in the core as shown in Table I. First, the temperature of the radiator panel is calculated by heat emission of radiator panels. Second, the temperature of the core is calculated from the temperature of the radiator panel and heat transfer resistance by heat transfer of heat pipes. The heat transfer resistance in terms of heat pipes is 9 types in total [5], and the sum of them is assumed as the total heat transfer resistance of heat pipes. The relationship of the temperature of the radiator panel and the total heat transfer resistance to the temperature of the core is shown in Eq. (1). As the result of the calculations, the maximum thermal power is 0.7 MW and the temperature of the core is 1336 K.

Table I. Melting Point of Materials in the core

	Material	Melting point [K]
Fuel	UC_2	2753
Cladding	Stainless steel	1370~1397
Structure	BeO	2843
Control rod	B_4C	3036

$$T_c = T_r + RQ \tag{1}$$

Where

T_c = the temperature of the core [K]
T_r = the temperature of the radiator panel [K]
R = the total heat transfer resistance [K/W]
Q = the thermal power of the core [W]

3.2 The number of heat pipes

The number of heat pipes can be calculated by the thermal power, the size, and the axial heat flux of heat pipe using the following equation (2). The axial heat flux of heat pipe becomes 9.75 kW/cm^2 when working fluid is Li and the temperature of the core is 1336 K. By using the values of the axial heat flux, and thermal power, and the cross section of heat pipe, 32 heat pipes are required in order to remove heat generated in the core.

$$N_{HP} = \frac{P_{core}}{q_{qx} A_{HP}} \tag{2}$$

Where

N_{HP} = the required number of heat pipes
P_{core} = the thermal power of the core
q_{ax} = the axial heat flux of heat pipe
A_{HP} = the cross section of heat pipe

4. Nuclear Design

In this chapter, the core to achieve the target value is designed based on the design method. First, the minimum critical mass is determined, the fuel lifetime is calculated, and the number of the control rods is investigated.

4.1 The minimum critical mass

The minimum critical mass is investigated from the calculation of the effective multiplication factor by changing the diameter of the structural material, height of the fuel and structural material, and the thickness of the reflector. The number of fuel pins and the ratio of fuel to structural material increase as the diameter of the structural material increases. With consideration of introducing the control rods, about 10 % of the total number of pins is left vacant for the control rods as shown in Fig. 1 and 32 heat pipes are inserted regularly into the center of the reflector in a radial direction. Fig. 2 shows the calculation result of the minimum critical mass. The effective multiplication factor from 1.02 to 1.06 is extrapolated as critical. These values are based on Refs. 1 and 6, Ref. 6 is a sample of a space nuclear that was designed as a fast reactor with high enriched uranium and rotating-type control rod system to control reactivity. The minimum critical mass is obtained for the core of each effective multiplication factor as shown in Table II. The mass of the critical core trends to decrease until the diameter and height of the structural material is 20 cm, and increase in excess of 20 cm. Though the core becomes critical with the thin reflector, more fuel is needed and the total critical mass becomes larger. It is valid to use the adequate thickness of the reflector in order to decrease the total mass of the core. In the next section, the fuel lifetimes of these five cores which have the minimum critical mass is investigated.

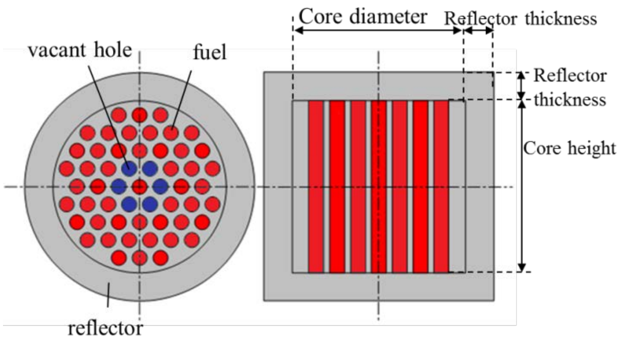

Fig. 1. Model of a small space reactor.

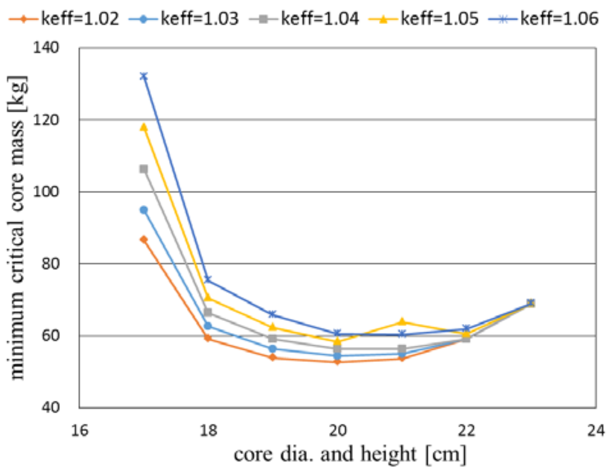

Fig. 2. Result of minimum critical mass.

Table II. Mass and Reflector of Critical Core

k-effective	1.02	1.03	1.04	1.05	1.06
Core diameter and height [cm]	20	20	20	20	21
Optimal Reflector thickness [cm]	1.9	2.1	2.4	2.6	2.0
Core total mass [kg]	44.2	54.5	56.3	58.3	60.4

4.2 Fuel lifetime

This section shows fuel lifetime of the five cases of the core with the minimum critical mass. The calculation is performed by burnup calculation to investigate how long the core keeps critical. As the condition of the burnup calculation, 0.7 MW of thermal power and 4000 days of burnup period are set respectively, and the temperature of the system is uniformly 1336 K over each calculation step. Fig. 3 shows the burnup calculation result for the five cases. The day when the effective multiplication factor is 1 corresponds to fuel lifetime of the core. The effective multiplication factors of any cores decrease as fuel period increases. The total core mass with 1.03 of the effective multiplication factor is the lowest of the cores whose fuel lifetime is more than 10 years, and 54.5 kg. This value of the total core mass is lower than the target value and fuel lifetime of the core is about 15 years. The required number of control rods is investigated in next section by the use of this core model.

4.3 The required number of control rods

The required number of control rods to keep critical is investigated by the effective multiplication factor calculation when the control rods are inserted into the vacant holes in the core. The calculation is performed at 1336 K. The maximum number of the control rods inserted into the core is 40 which is corresponding to the number of vacant holes. Fig. 4 shows the calculation result with the different number of control rods. The effective multiplication factor decreases as the number of control rods increase. When 40 control rods are inserted, the effective multiplication factor is about 0.95. It is possible to sufficiently control the criticality of this reactor by using forty control rods. However, when 15 control rods are used, the effective multiplication factor is less than 1. It is considered that it is possible to achieve subcriticality by using 15 control rods, but the core becomes subcriticality fully by using 40 control rods, and the safety design can be performed.

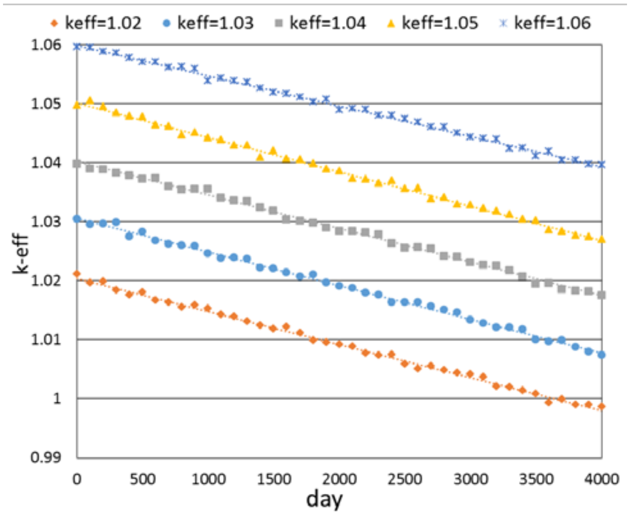

Fig. 3. Time variation of k-eff with different initial k-eff.

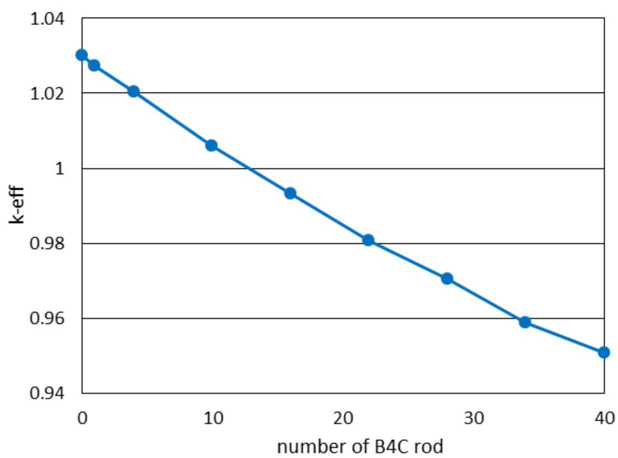

Fig. 4. Relationship with the number of B_4C rods and k-

eff.

Fig.5 shows the conceptual core design discussed in the chapters of thermal and nuclear design. The diameter and height of the core fuel part are 20 cm, the thickness of the reflector is 2.1 cm, and 40 control rods are inserted into the core with 1.03 of the first effective multiplication factor. By such a design, the size of the core is 24.2cm, the total core mass is about 54.5 kg, fuel lifetime is about 15 years when thermal power is 0.7 MW, and all target values are achieved.

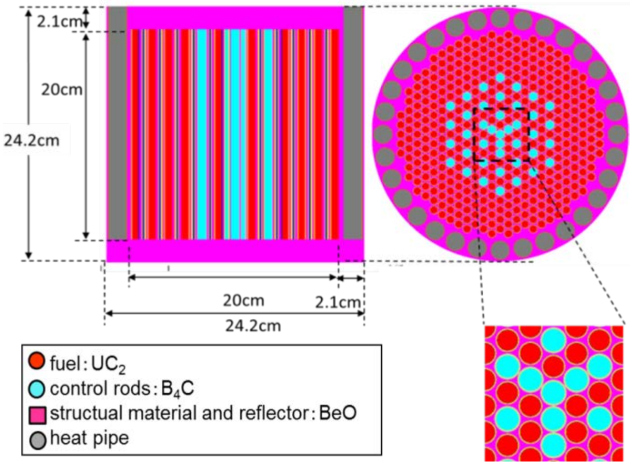

Fig. 5. Designed core in this study.

5. Conclusions

In this paper, a design study of small space reactor with high enriched uranium fuel was carried out in order to explore the possibility of the further reduction in size and weight of the reactor, the high power, and the long lifetime. In chapter 2, the design principle was determined, and the target values in terms of the mass and size of the core and thermal power were set. The detailed design of the heat pipe and the structural material employed in the reactor material were also determined. The procedures of the core design were mentioned about thermal and neutronics design respectively.

In thermal design, the temperature of the core, thermal power, and the number of heat pipes were set as the following value based on Eqs. (1), (2).

- Temperature: 1336 K (It's lower than 1370K that is melting point of the cladding.)
- Thermal power : 0.7 MW
- Number of heat pipes : 32

In neutronics design, the mass and size of the minimum critical mass, fuel lifetime of the minimum critical core, and the number of control rods ware set as below, by the calculation of the effective multiplication factor and burnup calculation.

- The total core mass : 54.5 kg
- The size of the core : 24.2 cm
- Fuel lifetime : about 15 years
- The number of control rods : 40

As above, the space reactor which fulfills all the demand of the total mass, the core size, and fuel lifetime was designed. There are the comparison of control methods, the discussion of the position of control rods and the number of vacant holes, and further detailed thermal design, as future tasks.

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