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A Feasibility and Optimization Study on a Small Space Reactor with 20w/o Uranium Fuel

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1. Introduction

As a part of the creative allied project (CAP), a small reactor, Korean Space Power Reactor (KSPR), with a thermal power of 5 kW is being studied at KAERI as a possible power supplier for deep space probe or orbiter. Other researchers have been developing small reactors for space applications. The US National Aeronautics and Space Administration (NASA) has been developing a small fast reactor called as fission power system (FPS) for deep space mission, where highly enriched uranium (HEU) is used as fuel.[1] On the other hand, other researchers have also surveyed a thermal reactor concept with low enriched uranium (LEU) for space applications. [2,3,4]

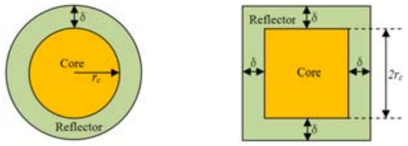
One of the main concerns in terms of a space reactor is the total mass of the reactor as well as the reactor size. In the US NASA FPS reactor, 93w/o enriched U-10Mo fuel with BeO reflector was used without moderator. The total mass of that reactor including the reflector was only 122.1kg and the outer radius of the reactor was as small as 16.5cm. The researchers in reference 2 and 3 concluded that they could achieve the reactor mass to be as low as 500kg with a combination of 20w/o enriched UN fuel, $YH_{1.5}$ moderator and Be reflector or with a combination of 20w/o enriched UO_2 fuel, H_2O moderator, and Be reflector.

In this paper, the results of feasibility and optimization studies on both simplified and realistic models of a small space reactor with LEU (20w/o) fuel are presented. All the neutronics analyses were done using the McCARD [5] code.

2. Methods and Results

2.1 Sensitivity Study and Optimization of a Reactor with 20w/o Enriched Uranium Fuel

It is well known that hydrogen is the best moderator to make a reactor core compact and the target operation temperature of KSPR is >600°C for high power conversion efficiency. Several materials were chosen as candidates for fuel, moderator, and reflector of KSPR : U-metal as fuel, $ZrH_{1.5}$ and LiH as moderator, Be and LiH as reflector. For the four combinations of the candidates, the critical core radius, r_c, and the total mass of the critical reactor including the reflector, m_{tot}, were calculated as functions of moderator to fuel ratio, $f=V_m/V_f$, and reflector thickness, δ, using the cylindrical core geometry shown in Fig. 1. The core was filled with a homogeneous mixture of fuel and moderator. Figure 2 shows the results for the combination of U fuel, $ZrH_{1.5}$ moderator, and Be reflector. For this case, the minimum reactor mass of 182.9 kg was achieved with f=15 and δ=3cm and the core radius was 14.83cm. Table I summarizes the optimal parameters for the four combinations. In the cases of LiH moderator, bare core was found to be optimal and the total reactor mass was only 77.5kg. However, the core configuration with $ZrH_{1.5}$ moderator and Be reflector was chosen for KSPR not only because $ZrH_{1.5}$ and Be are well proven materials for nuclear reactors but also because it is possible to keep the reactor temperature high.



(a) Top View (b) Side View

Fig. 1. Homogeneous Simple Reactor Model for Optimization

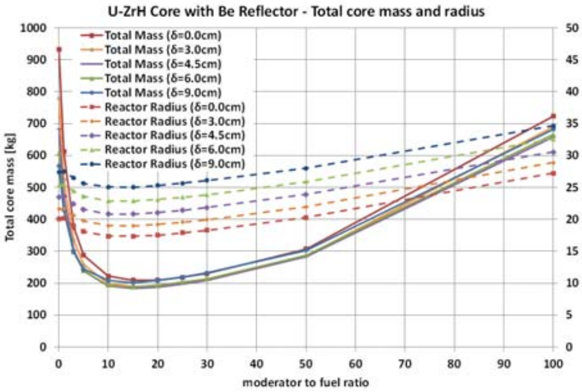


Fig. 2. Critical Core Radius and the Total Reactor Mass

Table 1. Optimal Core Configuration for the Four Cases

Mod./Refl.	$ZrH_{1.5}$	$ZrH_{1.5}$	LiH	LiH
Refl.	Be	LiH	Be	LiH
T_{mod}	<850°C	<850°C	<650°C	<650°C
T_{refl}	<1500°C	<650°C	<1500°C	<650°C
f_{opt}	15	15	30	30
δ_{opt}	3	4.5	0	0
$r_{c+}\delta$	17.8	19.4	21.3	21.3
m_{tot}	182.9	167.6	77.5	77.5

The sensitivity of the reactivity on the self-shielding of the fuel was also investigated as shown in Fig. 3. It was assumed that spherical uranium fuel particles were dispersed in $ZrH_{1.5}$ moderator and the radius of the fuel particles was changed while keeping the total amount of fuel in the core constant. The homogeneous case (r=0) in Fig 3 corresponds to the first case in Table I. The maximum reactivity of about 4609 pcm was achieved with a radius of 1mm.

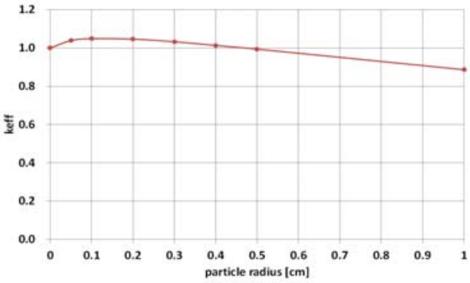


Fig. 3. The effect of self-shielding on the reactivity of the core

The temperature coefficient was investigated on the first case in Table I and it was found that temperature coefficient is strongly negative in the range of 300K ~1200K as shown in Fig. 4. The total temperature defect from 300K to 1200K was -5371 pcm. The thermal expansion effect was not considered in this calculation.

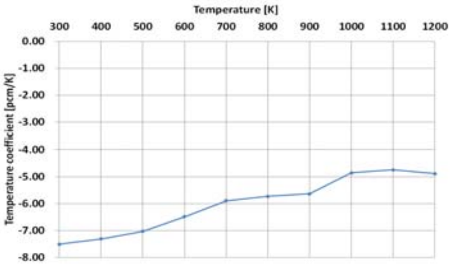


Fig. 4. Temperature Coefficient in the Range of 300K~1200K

Figure 5 shows the reactivity change for the first case in Table I during operation through 5000 effective full power days (EFPDs) at the power level of 5 kW$_{th}$. The reactivity swing was only 618pcm due to a very low power density of the reactor.

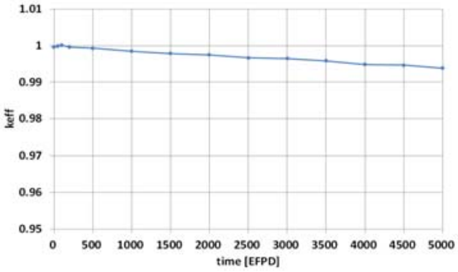
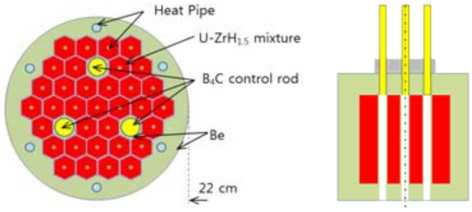


Fig. 5. Reactivity Change during Operation till 5000 EFPDs

2.2 A Realistic Model for KSPR

Based on the sensitivity and optimization study described in the previous section, a realistic model of the KSPR has been developed as shown in Figure 6 and Table II. The reactor core is composed of thirty four hexagonal fuel cells and three control rod cells and the core is surrounded by a Be container, which serves as a reflector too. The fuel cell is made of homogeneous mixture of U metal and ZrH$_{1.5}$ and a coolant hole is placed at the center of the fuel cell. Three B$_4$C control rods are installed at the control rod cell positions and NaK coolant is used.



(a) Top View (b) Side View

Fig. 6. Realistic Heterogeneous Core Configuration of KSPR

Table II. Key Design Parameters of KSPR

Thermal Power [kW$_{th}$]	5.0
Fuel Block Pitch [cm]	4.80
Active Core Height [cm]	33.30
Reflector Outer Radius [cm]	22.00
Reactor Total Mass [kg]	218
Excess Reactivity at 1200K (ARO) [pcm]	2010
Temp. Defect from 300K to 1200K (ARO) [pcm]	-4801
Control Rod Worth at 300K [pcm]	-12058
Core Reactivity with ARI at 300K [pcm]	-5248

3. Conclusions

In this paper, feasibility and optimization of a small space reactor with LEU (20w/o) fuel was studied. The results showed that ~78kg of reactor total mass was achievable in case of LiH moderator and ~183kg in case of ZrH$_{1.5}$ moderator with Be reflector. Based on these results, a realistic heterogeneous KSPR model with ZrH$_{1.5}$ moderator and Be reflector was developed. The total mass of the KSPR model was 218kg and the radius of the reactor was 22cm. More investigations including the thermal expansion effect on the reactivity, manufacturability of fuel cells with particulate uranium fuel, and accident analyses at launch will be performed for the KSPR model developed in this study in the future.

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