OPTIMIZATION OF THE MATERIAL COMPOSITION OF A SMALL SPACE REACTOR

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1. Introduction

Reliable, long-life power systems are required for ambitious space exploration missions. Space nuclear power options can be divided into three main categories: radioisotope power for heating or low power applications; fission power systems for non-terrestrial surface application or for spacecraft power; and fission power systems for electric propulsion or direct thermal propulsion. Each of these areas has been widely investigated since the 1950s, achieving various stages of development. [1] The biggest concern in terms of a space reactor is the total mass of the system. The designers of experimental and power reactors in Earth should not pay a special attention to issues connected with the size and the mass of their system, while a space reactor, which is fabricated in Earth, is strongly limited by transportation capacities. Proliferation is another significant issue, which should be addressed in an appropriate manner. The Korean Space Power Reactor (KSPR) [2] with a thermal power of 5 kW_{th} is being studied at KAERI [3] as a possible power supplier for deep space probe or orbiter. In this paper, the results of feasibility and optimization studies of the material composition on both simplified and realistic models of the KSPR, with (20w/o) fuel, are presented.

2. Calculation method

The presented study was performed in several steps. As the first step, the critical core mass and radius had to be determined for the homogeneous mixture of candidate materials, for various moderator-to-fuel ratios and reflector thicknesses. In the next step the fuel self-shielding effect was investigated for various designs. The simplified homogenous core model was further used to investigate the temperature reactivity coefficients and the fuel depletion. On the basis of the calculations performed on the homogenous core model a more detailed heterogeneous core design has been proposed. This core model was used for the development of the control rod design. All the calculations were performed by the stochastic Monte Carlo McCard [4] code with temperature dependent neutron cross-section libraries processed by the NJOY [5] evaluated data processing code.

3. Investigation of the critical core radius

The first step was to find out the radius of the core, the moderator-to-fuel ration and the thickness of the reflector (either radial or axial) that make the reactor critical while keeping the total mass of the system “as small as possible”. This step was carried out on a simplified model consisting of cylindrical homogenous core of fuel and moderator mixture surrounded by homogenous radial and axial reflector. The core model is shown in Fig.1, where “r_c” represents the radius of the reactor core and “δ” is the thickness of the reflector.

Fig.1: *The homogenous core model*

In each of the cases metallic uranium fuel with 19.5 %w of 235U was used. It is well known that hydrogen is the best moderator to make a reactor core compact and the target operation temperature of 600°C, thus four combinations of hydrogenous moderator materials were investigated. They were $ZrH_{1.5}$ and LiH with Be and LiH reflectors. In each case various moderator-to-fuel ratios (hereinafter "f") were investigated. To find the critical radius of the core for the given "f" and reflector thickness iterative calculation scheme utilizing the bisection and Newton methods was proposed. The plot of the total core mass and radius as a function of "f" for the most promising case is shown in Fig. 2.

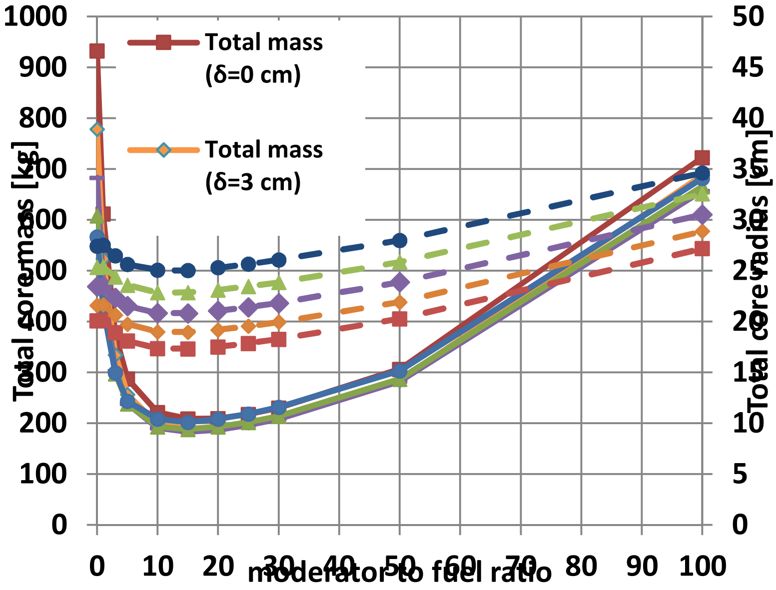

Fig.2: *Results of the $ZrH_{1.5}$ - Be core*

For the $ZrH_{1.5}$ - Be core, the minimum reactor mass of 182.9kg was achieved with *f*=15 and δ=3cm and the core radius was 14.83cm. In the cases with LiH moderator, bare core was found to be the most effective with the total mass of only 77.5kg. However, the core configuration with $ZrH_{1.5}$ moderator and Be reflector was chosen for further investigation not only because $ZrH_{1.5}$ and Be are well proven materials for nuclear reactors but also because $ZrH_{1.5}$ can withstand higher core temperatures.

4. Investigation of the fuel self-shielding

Two cases were examined, the one with fuel pins and the one with spherical particles (Fig. 3 - left). In both cases the total volumes of the fuel and the moderator were kept the same as in the most promising homogenous case. In the pin design the fuel pins were placed in hexagonal lattice. The radius of the fuel pin varied from 3.7 cm to 0.1 cm and it was calculated using Eq. 1, where "V_{core}" and "r_{core}" are the mass and the radius of the core respectively, "*PF*" the packing fraction (1/1+f) and "N_{pin}"is the total number of fuel pins. To keep the same pin height and volume the number of fuel pins varied from 1 to 853. In the second case it was assumed that spherical uranium fuel particles were dispersed in $ZrH_{1.5}$ moderator with the packing fraction of 0.0625 (f=15). The fuel volume was kept constant by changing the radius of the particles in a range of 1 to 0.05 cm and the number of particles from 306 to 2444251. The results are shown in Fig. 3 – right.

$$r_{pin} = \sqrt{\frac{V_{core}.PF}{2.\pi.r_{core}N^{i}_{pin}}} \tag{1}$$

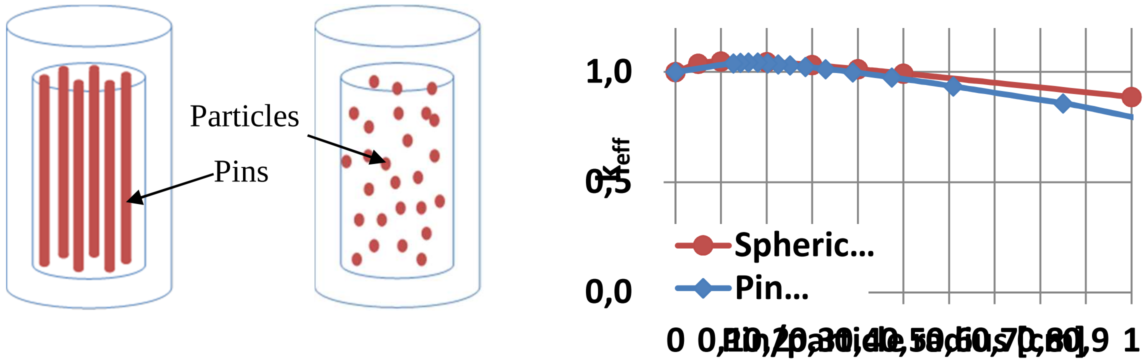

Fig.3: *Investigation scheme and results of the fuel self-shielding calculation*

The critical pin radius was at the level of 0.4cm and the spherical particles required 0.5cm. The maximum value of 4609pcm was found for particle radius 1mm, while the maximum for pins was about 300pcm less and required thinner fuel pins. Since the spherical particles could provide more reactivity and they are easier to fabricate then the thin fuel pins, the spherical particle design has been chosen as the basic design option.

5. Investigation the temperature reactivity coefficients and the burnup performance

The temperature reactivity coefficients were investigated on the homogenous core model. For every 100K temperature on a scale between 300-1200K a criticality calculation was performed, where the temperatures were set uniformly for all core materials. The k_{eff} results were graphically plot and a second order polynomial fit was used between three neighboring temperatures. The temperature coefficient was calculated as the derivative of the polynomial function. The total temperature defect over the temperature range was -5371pcm. The temperature coefficients were negative in every step and the average value of 6.01pcm/K was found. It can be concluded that the results are acceptable, however it should be noted that the thermal expansion effect was not considered in this calculation.

To assess the minimal excess reactivity required for 10 years of operation also the burnup performance had to be investigated. The burnup calculation was performed on the simple homogenous core model consisting of $UZrH_{1.5}$ fuel-moderator mixture with f=15 and 3cm thick solid axial and radial Be reflector. The reactor core was depleted through 5000 effective full power days at 5 kW_{th} reactor thermal power. Due to the very low power density of the reactor core the temperature defect was very low, only -618 pcm, which is about 45pcm per one effective full power year. Since the reactivity defect was not huge it can be concluded, that the given amount of core would be appropriate to provide the necessary excess reactivity for 10 or 15 years of operation at the given power level.

6. Realistic model of the space reactor

Based on the sensitivity and optimization study described in the previous section, a realistic model for KSPR was developed. Fig. 4 and Tab. 1 show the core configuration and key design parameters of the reactor, respectively. Thirty four hexagonal fuel blocks and three control rod blocks compose the core surrounded by Be container. The Be container roles 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 B4C control rods are installed at the control rod cell position. NaK is considered as coolant.

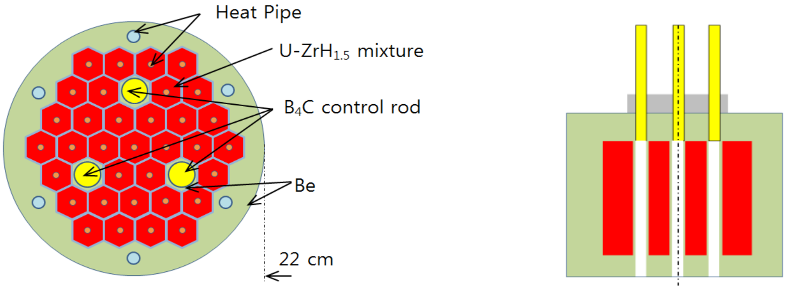

Fig.4: *Realistic heterogeneous core configuration of the KSPR*

Tab. 1. *Key design parameters of the KSPR*

Fuel Block Pitch [cm]	4.80
Active Core Height and Radius[cm]	33.3/22
Reactor Total Mass [kg]	218
Excess Reactivity at 1200K (rods out) [pcm]	2010
Temp. Defect from 300K to 1200K (rods out) [pcm]	-4801
Control Rod Worth at 300K [pcm]	-12058
Core Reactivity with all rods inserted at 300K [pcm]	-5248

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 can be 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 a fuel cell with particulate uranium fuel, and accident analysis at launch will be performed for the KSPR model developed in this study in the future.

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