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A Neutronic Feasibility Study on a Small LEU Fueled Reactor for Space Applications

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1. Introduction

A power supply system of a spacecraft plays a key role in deep space exploration missions. Possible energy sources for a spacecraft in the solar system are solar energy and nuclear energy. However, the solar energy density is too low to provide sufficient power required for exploring beyond Jupiter. For example, solar energy density near Saturn is as low as 1% of that near the Earth. Therefore, the only practically applicable option for the power supply of a spacecraft exploring beyond Jupiter or out of the solar system is nuclear energy. Nuclear power supply systems for space application can be classified into three categories [1]. The first one is a radioisotope power system for heating or low electric power. Their thermal power covers the W-range. The second one is a small fission power system for a spacecraft electric power supply, whose thermal power ranges in kW. The third one is a large fission power system for electric propulsion or direct thermal propulsion.

A small nuclear reactor with a thermal power of 5kWth is being studied at the Korea Atomic Energy Research Institute (KAERI) as a possible electric power supplier for a deep space probe. Many small fission reactors for space applications have been developed since the SNAP-10A reactor launched in 1965 [2]. Recently, the United States (US) National Aeronautics and Space Administration (NASA) and the Los Alamos National Laboratory (LANL) have been developing a small fission reactor, KRUSTY, with a fast neutron spectrum for deep space mission, where highly enriched uranium (HEU) is used as fuel [3]. On the other hand, other researchers have also surveyed a thermal reactor concept with low enriched uranium (LEU) for space applications [4,5,6]. One of the main concerns in terms of a space reactor design is the total reactor mass as well as the reactor size including the reflector. In the KRUSTY reactor design, 93 w/o enriched U-10Mo and BeO were used as the fuel and reflector materials, respectively. The total mass of the KRUSTY reactor including the reflector was only 122.1kg and the outer radius of the reactor was as small as 16.5cm. Kugo concluded that they could achieve a reactor mass as low as 500kg with a combination of 20 w/o enriched UN fuel, a $YH_{1.5}$ moderator and a Be reflector while Nishiyama estimated the reactor mass as low as 460kg when they combine 20 w/o enriched UO_2 fuel, a H_2O moderator, and a Be reflector.

In this paper, a feasibility study on a small space reactor with LEU fuel is presented. First, the minimum critical reactor mass and the corresponding reactor size for a homogeneous reactor geometry were investigated with the combinations of various fuel types, moderator materials, and reflector materials. The effect of the core heterogeneity on the reactor effective multiplication factor was also investigated. A neutronic feasibility study including a launch accident scenario analysis was also conducted for small space reactors with a control rod system and coolant pipes in the core. All calculations were performed using a Monte-Carlo code, McCARD [7] with continuous energy ENDF/B-VII.0 cross-section libraries.

2. Sensitivity Study on a LEU Fueled Small Space Reactor

2.1 Minimum Critical Mass of a LEU Fueled Homogeneous Reactor

The small fission power system, KRUSTY, which being developed by the NASA and LANL is a very compact reactor with a fast neutron spectrum because it utilizes HEU fuel without a moderator. On the contrary in this study, the focus was placed on the LEU fuel and thus the thermal reactor is very favorable from a neutronic point of view.

Almost all nuclear fuel types developed thus far, such as UO_2, UC, UN, UH_3, and U-metal, were considered and the ^{235}U enrichment was assumed to be 19.95% in this study. Metal hydrides were considered as a moderator since hydrogen is the best moderator to make a thermal reactor compact. The moderator materials considered are lithium hydride (LiH), alkaline earth metal hydrides (MgH_2 and CaH_2), ZrH_x, and YH_x. Water (H_2O) and hydro carbon materials such as polyethylene or oils were excluded because they are not feasible for a high temperature operation. Figure 1 compares the absorption cross-sections of the metal elements contained in the moderator materials. It was assumed that ^7Li in LiH is enriched to 99.99w/o to avoid high neutron absorption through a tritium production reaction of ^6Li. Natural Ca has a relatively large absorption cross-sections compared to ^7Li or natural Mg. Natural Y has a about seven-times larger thermal absorption cross-section than natural Zr. Lithium hydride (LiH) and alkaline earth metal hydrides (MgH_2 and CaH_2) have a very low thermal conductivity compared to ZrH_x or YH_x. Magnesium hydride (MgH_2) requires hydrogen pressurization for high temperature operation due to the very low hydrogen decomposition temperature. Zirconium hydride (ZrH_x) is a well proven moderator for a small thermal reactor for a space application since SNAP-10A utilized HEU as a fuel and ZrH_x as a moderator. Although the hydrogen to zirconium ratio, x, of ZrH_x used in the SNAP-10A reactor was 1.68 to 1.83 [8], a lower value of 1.5, was used in this study for conservatism. Beryllium (Be) and beryllium oxide (BeO) are also well proven reflector materials and are considered candidate reflector materials in this study.

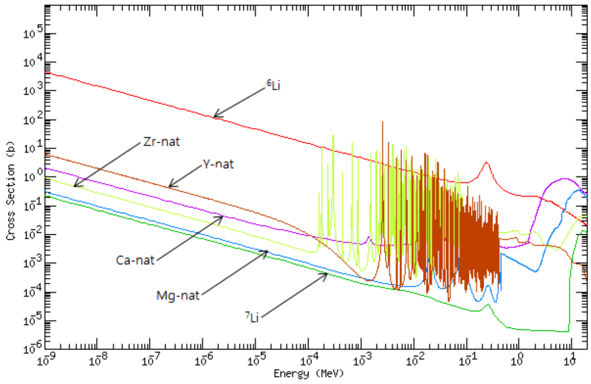


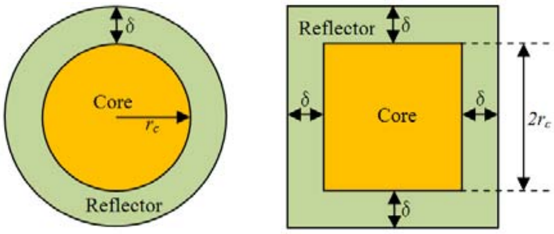
Figure 1. Comparison of Absorption Cross-sections of Some Metal Elements

Table I summarizes the properties of fuel, moderator, and reflector materials investigated. Lithium hydride (LiH) and calcium hydride (CaH_2) were chosen as moderator for the ceramic fuels (UO_2, UC, and UN) because their hydrogen decomposition temperatures are relatively high. The uranium hydride (UH_3) fuel requires hydrogen pressurization to prevent hydrogen release during high temperature operation due to its low hydrogen decomposition temperature. In spite of the low hydrogen decomposition temperature, magnesium hydride (MgH_2) was considered as the moderator for the UH_3 fuel in addition to LiH and CaH_2 under the condition that the core was pressurized. A porosity of 3% was considered for the fuel and moderator materials manufactured by sintering or powder pressing. Zirconium hydride (ZrH_x) and Yttrium hydride (YH_x) were chosen as the moderator for the U-metal fuel. A system temperature of 1000K was assumed.

Table I. Fuel, Moderator, and Reflector Materials

Material	Form	Density (g/cm^3)	H. Decomp. Temp. (°C)
UO_2	Powder	10.97	-
UC	Powder	13.63	-
UN	Powder	14.30	-
UH_3	Powder	10.95	~400
U-metal	Metal	19.10	-
LiH	Powder	0.78	~900
MgH_2	Powder	1.45	~300
CaH_2	Powder	1.70	~800
$ZrH_{1.5}$	Metal Hydride	5.60	~800
$YH_{1.5}$	Metal Hydride	4.20	~800
Be	Metal	1.85	-
BeO	Powder	3.01	-

Figure 2 illustrates the simple reactor geometry used in estimating the minimum critical reactor mass. The core is a homogeneous cylinder with a radius of r_c and a height to diameter ratio (H/D) of 1.0. The core is surrounded by a reflector with a thickness of δ. The core was assumed to be filled with a homogeneous mixture of fuel and moderator. For a given set of reflector thickness, δ, and a moderator to fuel volume ratio $f_m=V_m/V_f$, the critical core radius can be determined by adjusting the core radius. Once the critical core radius is determined, the critical reactor radius ($R=r_c+\delta$) and the critical reactor total mass (m_{tot}) including the reflector can be calculated.



(a) Top View (b) Side View

Figure 2. A Homogeneous Simple Reactor Geometry

Figure 3 shows R and m_{tot} as a function of δ and f_m for a UO_2-CaH_2 core with a Be reflector. The minimum critical reactor mass of 169.8kg was achieved with δ=6.94cm and f_m=9.01 and the critical reactor radius with these parameters was found to be 23.46cm. Figure 4 shows R and m_{tot} as a function of δ and f_m for UO_2-LiH core with a Be reflector. The minimum critical reactor mass of 70.1kg was achieved with δ=0.00cm and f_m=16.23, which means that a bare core is the best in terms of the reactor total mass when UO_2 and LiH are used as a fuel and moderator, respectively. The large difference in the minimum critical reactor mass of these two cases is attributed to the fact that the thermal absorption cross-section of natural Ca is much higher than that of ^{7}Li as shown in Figure 1 and the fact that the density per hydrogen of CaH_2 (1.70/2=0.85g/cm3) is higher than that of LiH (0.78 g/cm3). The cases with UC and UN fuel showed a very similar trend to the UO_2 fueled cases.

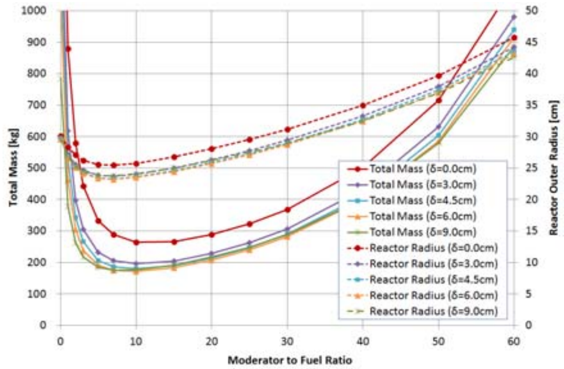


Figure 3. Critical Reactor Radius and Total Reactor Mass for a UO_2-CaH_2 Core with a Be Reflector

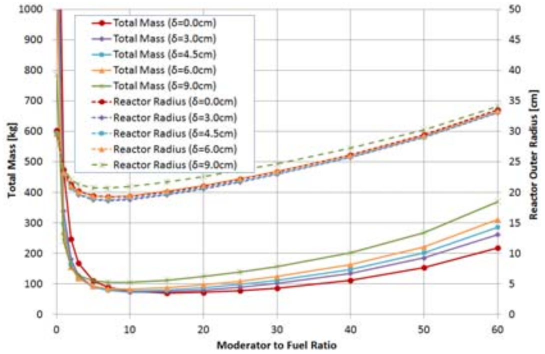


Figure 4. Critical Reactor Radius and Total Reactor Mass for a UO_2-LiH Core with a Be Reflector

Figure 5, 6, and 7 show R and m_{tot} for a UH_3-CaH_2 core, UH_3-LiH core, and UH_3-MgH_2 core with a Be reflector, respectively. Owing to the fact that the fuel itself has sufficient hydrogen, a very limited reduction of the reactor total mass or even mass increase was observed when the moderator was added. In the UH_3-CaH_2 case, a minimum total reactor mass of 68.2kg was achieved with δ=5.13cm and f_m=0.00. This means that adding a CaH_2 moderator does not help reduce the total reactor mass, which was attributed to a relatively large absorption cross-section of natural Ca and a high density per hydrogen of CaH_2 compared to those of LiH and MgH_2 (1.45/2=0.725g/cm3). On the contrary, a slight mass reduction was achieved by adding a LiH or MgH_2 moderator.

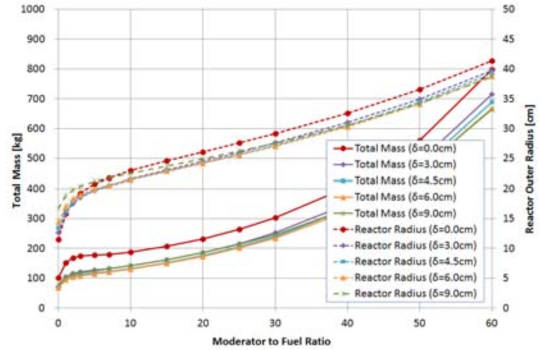


Figure 5. Critical Reactor Radius and Total Reactor Mass for a UH_3-CaH_2 Core with a Be Reflector

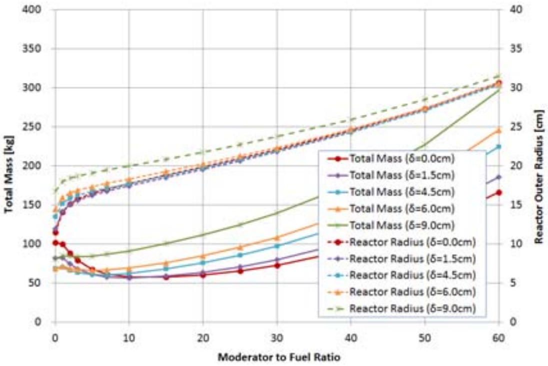


Figure 6. Critical Reactor Radius and Total Reactor Mass for a UH_3-LiH Core with a Be Reflector

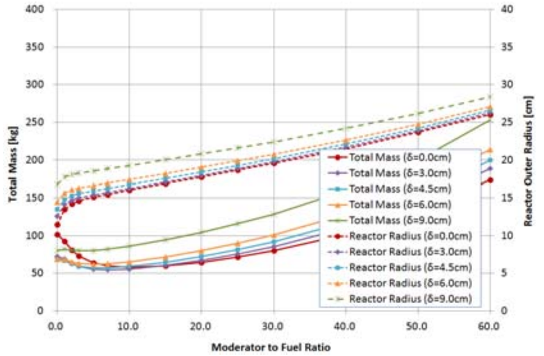


Figure 7. Critical Reactor Radius and Total Reactor Mass for a UH_3-MgH_2 Core with a Be Reflector

Figures 8 and 9 show *R* and m_{tot} for the U-$ZrH_{1.5}$ and U-$YH_{1.5}$ cores with a Be reflector, respectively. Despite that $ZrH_{1.5}$ has a higher density (5.6 g/cm3) than $YH_{1.5}$ (4.2 g/cm3), it was observed that $ZrH_{1.5}$ is much more effective moderator than $YH_{1.5}$ since natural Y has about a seven-times higher thermal cross-section than natural Zr as shown in Figure 1.

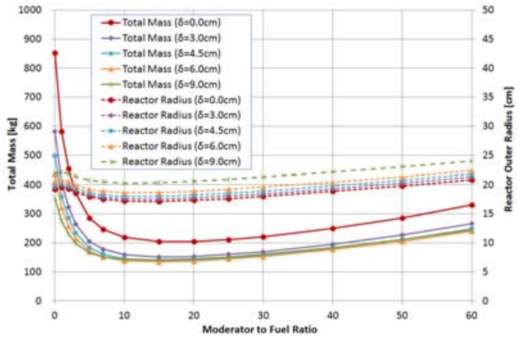


Figure 8. Critical Reactor Radius and Total Reactor Mass for a U-$ZrH_{1.5}$ Core with a Be Reflector

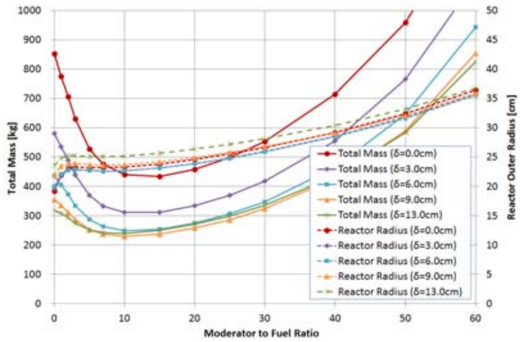


Figure 9. Critical Reactor Radius and Total Reactor Mass for a U-$YH_{1.5}$ Core with a Be Reflector

Table II summarizes the optimum δ and f_m values with which the critical reactor mass is at minimum as well as the corresponding critical core radius, critical reactor radius, and minimum critical reactor mass for eleven combinations of fuels and moderators with a Be reflector. The use of a BeO reflector instead of a Be reflector increases the total critical reactor mass while the reactor radius remains similar, as shown in Table III. Although the focus of this study was placed on the LEU fuel, it is worth investigating some cases with HEU fuels. Figure 10 shows R and m_{tot} for a highly enriched (93w/o) U-$ZrH_{1.5}$ core with a Be reflector. From Figure 10, it is clear that no moderator is needed and the core with a fast neutron spectrum is favorable in terms of reactor mass when HEU metal is used as a fuel. Table IV summarize the results of the eleven combinations of fuel types and moderators with a Be reflector. The minimum reactor mass was achieved with f_m=0.00 for all cases.

Table II. Optimal Parameters for the Cores with a Be Reflector

Case	Fuel	Mod.	f_m	δ (cm)	r_c (cm)	R (cm)	m_{tot} (kg)
1	UO_2	CaH_2	9.01	6.94	16.52	23.46	169.8
2	UO_2	LiH	16.23	0.00	20.32	20.32	70.1
3	UC	CaH_2	11.65	7.18	16.01	23.20	163.5
4	UC	LiH	20.74	0.00	20.02	20.02	67.0
5	UN	CaH_2	12.30	7.53	16.13	23.67	173.1
6	UN	LiH	21.48	0.00	20.28	20.28	70.3
7	UH_3	CaH_2	0.00	5.13	8.76	13.89	68.2
8	UH_3	LiH	10.40	1.50	15.90	17.40	55.5
9	UH_3	MgH_2	7.54	2.59	13.13	15.72	54.2
10	U	$ZrH_{1.5}$	15.45	6.45	12.45	18.90	133.8
11	U	$YH_{1.5}$	10.94	9.41	14.52	23.93	228.5

Table III. Optimal Parameters for the Cores with a BeO Reflector

Case	Fuel	Mod.	f_m	δ (cm)	r_c (cm)	R (cm)	m_{tot} (kg)
1	UO_2	CaH_2	9.86	4.77	18.38	23.15	213.9
2	UO_2	LiH	16.23	0.00	20.32	20.32	70.1
3	UC	CaH_2	12.19	5.11	17.61	22.72	205.3
4	UC	LiH	20.74	0.00	20.02	20.02	67.0
5	UN	CaH_2	13.04	4.74	18.54	23.29	219.2
6	UN	LiH	21.48	0.00	20.28	20.28	70.3
7	UH_3	CaH_2	0.00	3.66	9.10	12.76	75.4
8	UH_3	LiH	15.00	0.00	18.30	18.30	52.9
9	UH_3	MgH_2	10.99	0.00	16.18	16.18	57.9
10	U	$ZrH_{1.5}$	15.43	4.71	13.18	17.88	157.2
11	U	$YH_{1.5}$	11.00	6.92	15.83	22.75	283.3

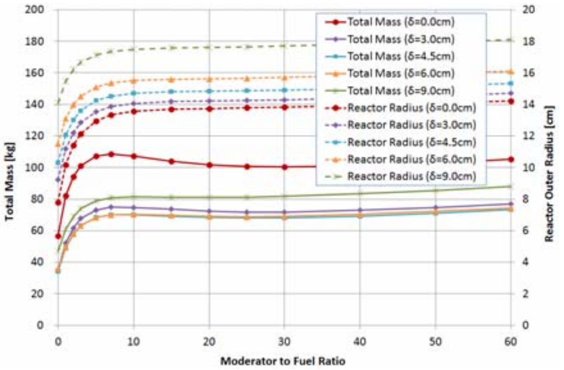


Figure 10. Critical Reactor Radius and Total Reactor Mass for a HEU-$ZrH_{1.5}$ Core with a Be Reflector

Table IV. Optimal Parameters for the HEU Fueled Cores with a Be Reflector

Case	Fuel	δ (cm)	r_c(cm)	R (cm)	m_{tot} (kg)
1-2	UO_2	6.16	8.78	14.94	76.1
3-4	UC	5.26	7.50	12.76	54.3
5-6	UN	5.47	7.51	12.98	57.5
7-9	UH_3	2.95	5.92	8.87	20.0
10-11	U	4.39	5.84	10.23	34.0

From Table II, it is clear that LiH with 99.99w/o enriched ^{7}Li and MgH_2 are very good moderators from a neutronic point of view. However, the thermal properties of LiH are quite poor. The melting point is 962K, which is quite low compared to the target operating temperature (>1000K). The thermal conductivity is ~3W/m•K at 1000K [9], which is comparable with that of UO_2 but about seven-times lower than that of UC, UN, or zirconium. Moreover, the linear thermal expansion coefficient is about 4×10-5/K at room temperature [10], which is about three-, four-, and seven-times larger than that of uranium, beryllium, and zirconium, respectively. The thermal stress at hot full power condition can be an issue when LiH is used as a moderator. The hydrogen decomposition temperature of MgH_2 is quite low, as shown in Table I, and it can be used as moderator only when the reactor is pressurized with hydrogen gas. Uranium hydride, UH3, is a very attractive fuel from a neutronic point of view. However, it requires hydrogen pressurization for high temperature operation due to its low hydrogen decomposition temperature, which inevitably introduces additional reactor components such as a thick pressure vessel and pressurizer, and, in turn, an additional reactor mass. In order to adopt LiH, MgH_2, and UH_3 as a moderator and fuel, a study on a special design concept should be conducted to overcome the problems mentioned above. On the contrary, U-ZrH_x is a well proven material for small thermal reactors for space application since SNAP-10A. Therefore, a neutronic analyses only with the combination of a U-metal fuel, $ZrH_{1.5}$ moderator, and Be reflector have been performed and will be discussed in the following sections.

2.2 Heterogeneity Effect in a LEU Fueled Small Reactor

Figure 11 illustrates a heterogeneous core configuration. Unlike the homogeneous case, the core is composed of fuel plates and moderator plates stacked one after the other. For a fixed moderator to fuel ratio, the heterogeneity decreases as the number of fuel plates increases and the homogeneous case is an extreme case where the number of fuel plates goes to infinity. Figure 12 compares the neutron spectra in the core region for the three cases with the same values of moderator to fuel ratio (f_m=15.45), reflector thickness (δ=6.45cm), and core radius (r_c=12.45cm) as in case 10 of Table II. As the number of fuel plates decreases, the thickness of the fuel and moderator plates increases as does the core heterogeneity. The more heterogeneity the core has the softer the neutron spectrum becomes. Figure 13 shows the effect of core heterogeneity on the effective multiplication factor of the U-metal fueled, $ZrH_{1.5}$ moderated, and Be reflected core. The maximum core reactivity (about +3,000pcm) is achieved when the fuel plate thickness is about 0.75mm which corresponds to 20 fuel plates while the homogeneous reactor was only critical with exactly the same mass of fuel, moderator, and reflector materials.

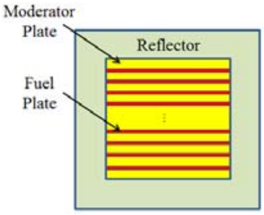


Figure 11. Side View of the Heterogeneous Reactor Geometry

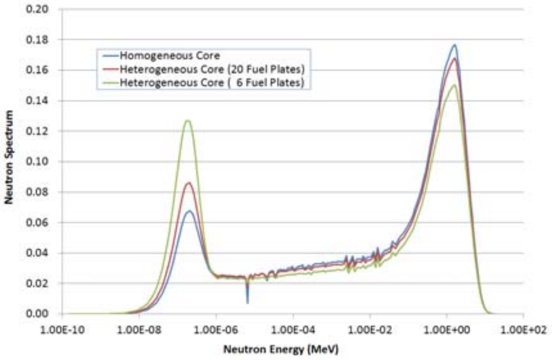


Figure 12. Comparison of Core Spectra

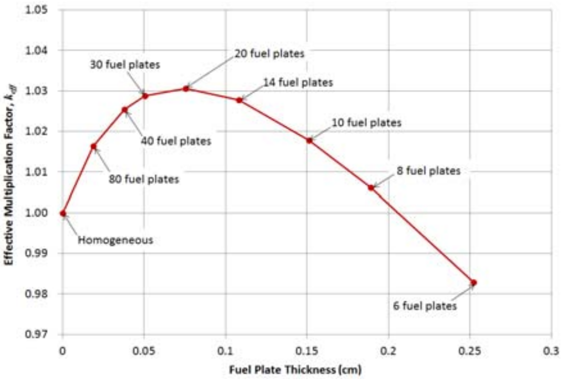


Figure 13. Effect of Core Heterogeneity on the Effective Multiplication Factor

Generally speaking in case of thermal reactors, the resonance escape probability (p ; the probability that a fast neutron is not absorbed by a resonance absorber during its slowing down) increases as the heterogeneity increases since the neutrons have less chance to meet fuel, a resonance absorber, during its slowing down which happens mainly in the moderator when fuel and moderator are separated. The increase of the resonance escape probability results in an increase of the thermal neutron population. This phenomenon explains the spectrum change shown in Figure 12. On the other hand, the thermal utilization factor (f ; the probability that a thermal neutron absorbed was absorbed in the fuel) decreases as the heterogeneity increases because the fuel absorption reaction decreases as the fuel becomes thicker due to the spatial self-shielding of the fuel. Moreover, in this reactor, the fast non-leakage probability (P_f ; the probability that a fast neutron does not leak out from the core) increases and the thermal non-leakage probability (P_t ; the probability that a thermal neutron does not leak out from the core) decreases as the number of fuel plates decreases because the neutron spectrum at the axial core-reflector boundary as well as the core average spectrum become softer due to the thick moderator plates at the top and bottom of the core. On the contrary, the fast fission factor (ε ; the ratio of total fission to thermal fission) and the reproduction factor (η ; the number of fission neutrons per neutron absorption in the fuel) remains almost constant regardless of the thickness of the fuel plate. Figure 14 shows some of the "six factors" as a function of fuel plate thickness. The combined effect of the phenomena described above resulted in the core reactivity behavior shown in Figure 13. Figure 13 also implies that we can reduce the total reactor mass by adopting a heterogeneous core design. For example, we can make a heterogeneous critical reactor with 20 fuel plates by reducing the core radius. The critical core radius for the case with f_m=15.45 and δ=6.45cm is 11.85cm and the total reactor mass is 119.6kg while those of the homogeneous case were 12.45cm and 133.8kg, respectively as listed in Table V.

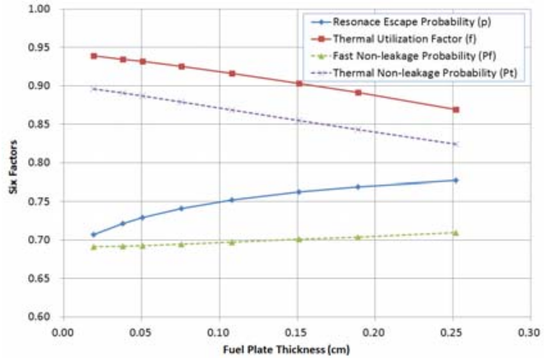


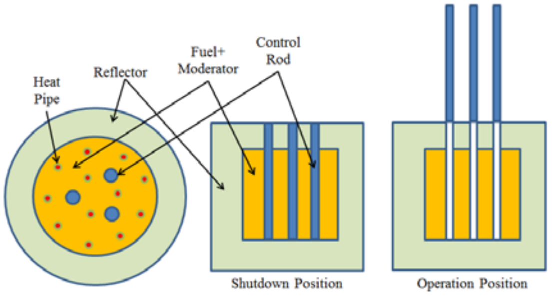
Figure 14. The Six Factor as a Function of Fuel Plate Thickness

Table V. Comparison of Homo. and Hetero. Critical Reactor

Parameters	Homogeneous	Heterogeneous
Fuel Material	LEU metal	LEU metal
Moderator Material	$ZrH_{1.5}$	$ZrH_{1.5}$
Reflector Material	Be	Be
Reflector Thickness (cm)	6.45	6.45
Moderator to Fuel Ratio, f_m	15.45	15.45
Number of Fuel Plates	-	20
Fuel Plate Thickness (cm)	-	0.07226
Moderator Plate Thick. (cm)	-	1.060
Critical Core Radius (cm)	12.45	11.85
Critical Reactor Mass (kg)	133.8	119.6

3. Neutronic Feasibility Study on a LEU Fueled Small Space Reactor

In this section, the results of a feasibility study with a more realistic reactor model introducing a control rod system and coolant pipes in the core will be presented. Figure 15 illustrates the radial and axial cross-sections of the small space reactor with a control rod system and coolant pipes. Three cases depending on the core heterogeneity and the reflector thickness were investigated. The first and second cases, marked as case A and B, adopted a homogeneous core configuration while the third case, case C, adopted a heterogeneous core configuration with fuel and moderator plates. The reflector thickness in case A was 6.45cm, the optimal thickness listed in case 10 of Table II, while in cases B and C thicker reflectors were used to make the reactor subcritical in the various accident scenarios described below. The design parameters for these three cases are listed in Table VI. In cases B and C, smaller core radii than in case A were achieved as a result of the thicker reflector. Compared to the other cases, a larger volume of control rod absorbers and higher ^{10}B enrichment were required in case A to obtain sufficient control rod worth when it is immersed in water or wet sand. The absorber of the control rods are canned with 1mm thick Be metal. The total reactor mass of the three cases is higher than the minimum critical reactor mass in case 10 of Table II. The mass increase can be attributed to the following three factors. The first one is the increase of the core radius due to internal core structures such as control rods and heat pipes and the second one is additional core mass for excess reactivity and the third one is the thicker reflector for safety. The fuel mass in cases B and C is about a half of that in case A due to a smaller core size. Among these three cases, the heterogeneous case (case C) has the smallest mass, which is about 54kg lighter than the reactor mass in case B with a similar neutronic performance and reactivity behavior during various accident scenarios.



(a) Top View (b) Side View

Figure 15. Geometry of a Small Space Reactor with a Control Rod System and Coolant Pipes

Table VII shows the neutronic performance of the reactors during their life time. The standard deviations of the effective multiplication factors are around 10 pcm. At the beginning of life (BOL), the reactors in all cases have a sufficient control rod worth to grant subcriticality. In case A, the control rod worth was about 21,000pcm while in cases B and C it was about 16,000pcm. The temperature defects from the cold zero power state (CZP, 300K) to hot full power state (HFP, 1100K) in the homogeneous cases (cases A and B), are -4,800pcm and -4900pcm, respectively while it was about -3,300pcm in case C. The large difference in the temperature reactivity defect between the homogeneous and the heterogeneous cases can be attributed to the difference of resonance escape probability. The heterogeneous case has larger resonance escape probability than the homogeneous ones, which means that less neutrons are absorbed in the resonances of the fuel and, in turn, less Doppler effect is induced when the core temperature increases. The leakage effect due to the thermal expansion is quite important in a small reactor and the reactivity defect due to thermal expansion was about -1,400pcm ~ -1,500pcm for all the three cases when a thermal expansion of 1% was considered. The reactivity swing during the life time was about -700pcm in case A, but was about -1,100pcm in the other two cases due to a smaller fuel inventory. The excess reactivity at the end of life time was about 600pcm ~ 700pcm for all the three cases.

Table VI. Design Parameters of the Space Reactors with a Control Rod System and Coolant Pipes

Parameters	Case A	Case B	Case C
Thermal Power (kW)	5.0	5.0	5.0
Life Time (year)	15.0	15.0	15.0
Operation Temperature (K)	1100	1100	1100
Fuel Material	LEU	LEU	LEU
Moderator Material	$ZrH_{1.5}$	$ZrH_{1.5}$	$ZrH_{1.5}$
Reflector Material	Be	Be	Be
Active Height/Diameter Ratio	1.00	1.00	1.00
Number of Control Rods	3	3	3
Control Rod Can Thickness (cm)	0.10	0.10	0.10
Control Rod Gap Thickness (cm)	0.05	0.05	0.05
Control Rod Can Material	Be	Be	Be
Number of Heat Pipes	12	12	12
Heat Pipe Inner Radius (cm)	0.4	0.4	0.4
Heat Pipe Thickness (cm)	0.1	0.1	0.1
Heat Pipe Material	Zr	Zr	Zr
Coolant Material	NaK	NaK	NaK
Control Rod Position (cm)	7.42	5.80	5.90
Inner Heat Pipe Position (cm)	4.94	3.87	3.93
Outer Heat Pipe Position (cm)	13.83	10.60	10.80
Control Rod Absorber Radius (cm)	2.30	1.60	1.50
Control Rod Absorber Material	B_4C	B_4C	B_4C
^{10}B Enrichment in B_4C (w/o)	89.11	18.43	18.43
Moderator to Fuel Ratio, f_m	15.45	15.45	15.45
Core Heterogeneity	Homo.	Homo.	Hetero.
Number of Fuel Plates	-	-	20
Reflector Thickness (cm)	6.45	14.20	11.30
Core Radius (cm)	14.83	11.60	11.80
Fuel Mass (kg)	21.52	10.36	11.03
Moderator Mass (kg)	97.49	46.91	49.94
Reflector Mass (kg)	73.20	180.23	123.25
Reactor Total Mass (kg)	197.1	240.8	187.1

Table VII. Neutronic Performance of the Space Reactors with a Control Rod System

Reactor State	Rod Position	k_{eff}		
		Case A	Case B	Case C
BOL, CZP	Shutdown	0.88247	0.92634	0.91413
BOL, CZP	Operation	1.08213	1.08946	1.07134
BOL, HFP [a)]	Operation	1.02856	1.03429	1.03453
BOL, HFP [b)]	Operation	1.01385	1.01925	1.01857
EOL, HFP [b)]	Operation	1.00712	1.00742	1.00702

a) No thermal expansion was considered.
b) A thermal expansion of 1% was considered.

The space reactor should not be critical during launch accidents such as rocket explosion, re-entry, or crash on the ground or in the ocean. Table VIII shows the results of launch accident scenario analyses performed for the three cases. The standard deviations of the effective multiplication factors were around 10pcm but they were omitted from Table VIII. The coolant holes and He gaps were assumed to be filled with surrounding materials (water, wet sand, or dry sand) except for the "As Launched" scenarios in Table VIII. It was also assumed that the holes of the missing control rods were filled with surrounding materials. The dry and wet sand were assumed to be SiO_2 with 36% porosity and a homogeneous mixture of 64% SiO_2 and 36% water, respectively. A water density of 1.0g/cm^3 was also assumed. The effective multiplication factor is less than 0.98 in all scenarios for cases B and C. On the contrary, it showed out that the reactor in case A becomes supercritical if the reflector and the control rods are lost while the effective multiplication factor remains less than 0.98 when the reactor has no or minor damage. The core size in case A is quite large compared to the other two cases and the core itself can be supercritical without a reflector when the control rods are missing and the core is surrounded by water or wet sand.

Table VIII. Accident Scenario Analysis of the Space Reactor with a Control Rod System

Accident Scenario			k_{eff}		
			Case A	Case B	Case C
In Water	No Damage in Reflector	As Launched	0.97012	0.96793	0.96605
		Cool. Pipe Broken	0.97591	0.97578	0.97311
	Reflector Missing	No CR Missing	0.88464	0.80520	0.81631
		One CR Missing	0.98578	0.87163	0.87930
		Two CRs Missing	1.05595	0.92660	0.93213
		All CRs Missing	1.11571	0.97556	0.97950
In Wet Sand	No Damage in Reflector	As Launched	0.97491	0.96801	0.96656
		Cool. Pipe Broken	0.97785	0.97189	0.97053
	Reflector Missing	No CR Missing	0.89200	0.80126	0.81621
		One CR Missing	0.98382	0.86055	0.87383
		Two CRs Missing	1.05372	0.91307	0.92512
		All CRs Missing	1.11540	0.96189	0.97268
In Dry Sand	No Damage in Reflector	As Launched	0.96151	0.96010	0.95715
		Cool. Pipe Broken	0.96269	0.96120	0.95874
	Reflector Missing	No CR Missing	0.82966	0.70896	0.73820
		One CR Missing	0.91210	0.76041	0.78936
		Two CRs Missing	0.98000	0.80774	0.83639
		All CRs Missing	1.04198	0.85338	0.88119

Although many launch accident scenarios were investigated in Table VIII, the worst-case scenarios in which some or all the control rods are missing without any damage in the reflector were not considered in Table VIII. Table IX shows the results of the worst-case accident scenario analysis. The results are showing that the loose of a single control rod can result in a supercritical core state in all three cases. However, such a situation is inevitable as long as a conventional control rod system is used as reactivity control system. This situation would be similar even if a conventional control drum system [11] is adopted instead of a control rod system. If some or all of the control drums were missing without any damage in the reflector, the reactor with a conventional control drum system should become supercritical. A study on an accident-tolerant reactivity control system should be conducted to overcome this drawback of conventional reactivity control systems.

Table IX. The Worst-case Accident Scenario Analysis of the Space Reactor with a Control Rod System

Accident Scenario			k_{eff}		
			Case A	Case B	Case C
In Water	No Damage in Refl.	One CR Missing	1.08396	1.05174	1.04504
		Two CRs Missing	1.15981	1.11709	1.10690
		All CRs Missing	1.22503	1.17690	1.16334
In Wet Sand	No Damage in Refl.	One CR Missing	1.07480	1.03975	1.03634
		Two CRs Missing	1.14868	1.10094	1.09530
		All CRs Missing	1.21389	1.15869	1.15065
In Dry Sand	No Damage in Refl.	One CR Missing	1.04927	1.02252	1.01898
		Two CRs Missing	1.11921	1.07922	1.07447
		All CRs Missing	1.18260	1.13419	1.12737

4. Conclusions

In this paper, a neutronic feasibility study on a small space reactor with LEU fuel was presented. The minimum critical reactor mass with a simple geometry model was investigated for the combinations of various fuel types, moderator materials, and reflector materials. Lithium hydride (LiH) with 99.99% enriched ^{7}Li showed a very good performance in terms of reactor mass. The minimum critical reactor mass was around 70kg when 99.99% enriched ^{7}LiH was combined with ceramic fuels (UO_2, UN, or UC) and a Be reflector. However, further study should be conducted to resolve the problems that could arise from the poor thermal properties of LiH such as a low melting point, low thermal conductivity, and high thermal expansion coefficient. The combination of uranium metal fuel and Zirconium hydride ($ZrH_{1.5}$) moderator with a Be reflector also showed a good performance and the minimum critical reactor mass was 133.8kg. Uranium hydride (UH_3) is a very attractive fuel from a neutronic point of view. However, it requires hydrogen pressurization for high temperature operation due to its low hydrogen decomposition temperature. The effect of the core heterogeneity was also investigated. Either the core reactivity can be maximized or the critical reactor mass can be minimized by stacking thin U-metal fuel plates and $ZrH_{1.5}$ moderator plates one after the other.

Based on the sensitivity study, three small space reactors with a control rod system and NaK coolant pipes were designed and the neutronic performance of these reactors during their life time as well as their safety behavior during various accident scenarios was also investigated. A homogeneous core was adopted in the first and second cases, cases A and B, while a heterogeneous core with fuel plates and moderator plates was adopted in case C. The reflector in case A was much thinner than that in the other cases. The reactor total mass in case C was the smallest among the three cases. The reactors in all cases showed similar neutronic performance during their life time. The reactor with a thin reflector in case A became supercritical when the reflector and some or all of the control rods are missing, while the reactors with a thick reflector in cases B and C remain subcritical (k_{eff}<0.98) in the same conditions. However, even the reactors in cases B and C became supercritical in the worst-case accident scenarios in which some or all of the control rods are missing without any damage to the reflector. Such situation is inevitable as long as a conventional control rod system or control drum system is adopted as the reactivity control system of the reactor. A study on an accident-tolerant reactivity control system should be conducted to overcome this drawback of a conventional reactivity control system.

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