A Conceptual Study on a Supercriticial CO_2-cooled KAIST Micro Modular Reactor

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1. Introduction

Small Modular Reactors (SMRs) are nuclear reactors that are completely built in a factory and shipped to the designated site for installation. As such, the SMR is especially advantageous as a flexible and cost-effective energy source for remote and isolated areas. Furthermore, the concept requires a relatively low capital cost, which makes it attractive for developing countries with limited electricity grid. In addition, the SMR concepts also generate more interest after the Fukushima accident since it can easily be designed with a passive decay heat removal system.

One of the major advantages of a water-cooled SMR is its relatively small core size. Nonetheless, in spite of its small core size, the volume and area required for its steam-cycle power conversion unit is still significant. Therefore to significantly reduce size of its power conversion unit, a new SMR concept named KAIST micro-modular reactor (MMR) that uses supercritical CO_2 (S-CO_2) as coolant was recently proposed. This concept takes advantage of the higher thermal efficiency of S-CO_2 Brayton cycle, compared to that of the steam cycle [1,2].

This paper presents the neutronics study of the KAIST MMR design. The reactor thermal power was determined to be 36.2 MWth with an active core 1.2 m in height and 93.16 cm in diameter. Size of the whole core including its reactor shield was 2.8 m in height and 164 cm in diameter, resulting in total mass of the reactor about 39.6 tons. The reactor is fast spectra-dominant and transportable as a fully compact integral reactor in which reactor core, power conversion unit, and safety systems are contained in a single pressure vessel as depicted Fig.1. Targeted design lifetime of the KAIST MMR is 20 EFPYs (Effective Full Power Years).

To transport the integral reactor efficiently, its total weight must be minimized. This calls for a core that is as compact as possible. This inadvertently limits amount of fuel available and increases neutron leakage out of the core, requiring sufficient radiation shield surrounding the core. The KAIST MMR core was therefore designed with 20 cm-thick PbO reflector and 10 cm-thick natural B_4C shield. The reflector-shield layer should be sufficient to ensure safe radiation limit of the KAIST MMR. Nevertheless, detailed radiation analysis of the design will be performed in future study.

All neutronic analyses in this study were completed using the Monte Carlo code Serpent [3] with ENDF/B-VII.0 neutron data library.

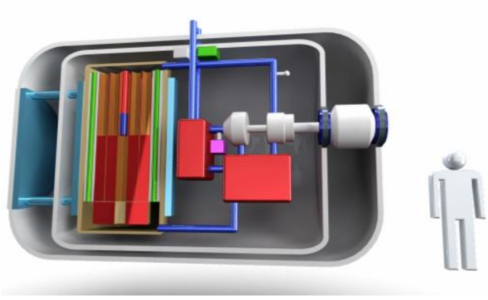


Fig. 1. Schematic figure of KAIST MMR

2. KAIST MMR Design Concept

2.1 Enriched Uranium nitride fuel

In this study, UN fuel was used for its high density (13.55 g/cc) which subsequently increases available uranium inventory, compared to UO_2 ceramic fuel (10.97 g/cc) and U-Zr metallic fuel. In addition, UN has also notable fuel performance properties such as high melting temperature and high thermal conductivity which is comparable to that of a metallic fuel. As such, the UN fuel can significantly improve the reactor operational safety margins, offer more flexibility in reactor power maneuvers, and provide better value of fuel cycle economics [4].

However, due to the high (n, γ) and (n,p) cross sections of ^{14}N, the nitride in the UN should be enriched to ^{15}N to enhance the neutron economy. Fig. 2 shows the comparison of (n, γ) and (n,p) cross sections between ^{14}N and ^{15}N based on ENDF/B-VII.0 [5].

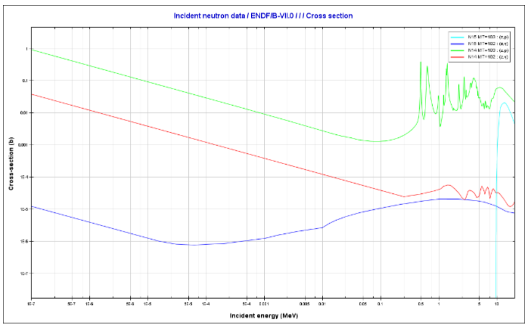


Fig. 2. Comparison of ^{14}N and ^{15}N (n,γ) and (n,p) cross section [5]

Fuel swelling is one of the major concerns with the UN fuel utilization. In this study, 95% smear density was assumed for the $U^{15}N$ fuel to deal with the irradiation swelling of UN fuel. Figure 3 shows the predicted UN fuel swelling as a function of volume-averaged fuel temperature and atomic burnup [6]. One notes at 5.1% average discharge burnup and 975.2 K average fuel temperature, the fuel swelling was predicted to be less than 5%.

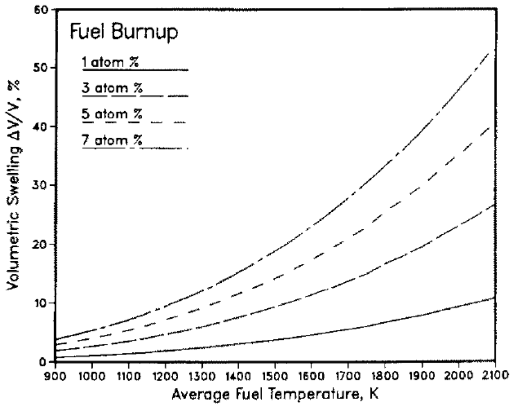


Fig. 3. Predicted UN fuel swelling against volume-averaged fuel temperature [6]

2.2 Concepts of the KAIST MMR Core

Figure 4 and Table 1 summarize the design configurations of the KAIST MMR core. The core consisted of 18 fuel assemblies, 12 primary control drums and one secondary shutdown rod, reflector and shield. Each fuel assembly is comprised of 127 fuel pins, with 1.5 cm pin diameter and P/D at 1.13. The fuel pin was uranium enriched mono-nitride ($U^{15}N$). Cladding material was 0.05 cm thick, and made from ODS steel (oxide dispersion-strengthened), which has improved material properties compared to stainless steel 316, such as creep resistance of up to 800°C [4]. The flat-to-flat fuel assembly distance is 20.105 cm. Volume fractions of fuel, gap, coolant, and structure are 52.94%, 1.546%, 30.66% and 14.855%, respectively.

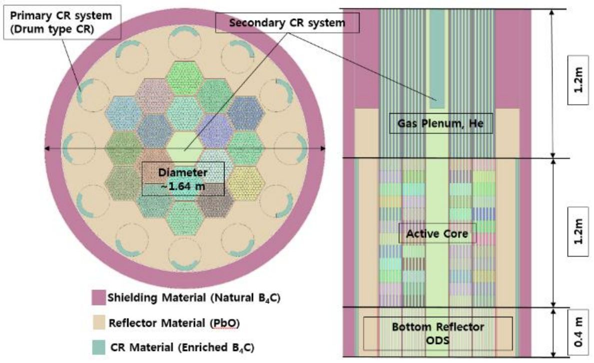


Fig. 4. Radial and axial configurations of MMR core

Table. 1. Design parameters of KAIST MMR

Parameter	Value
Rector Power/Life time	36.2 MWth / 20 years
Number of FAs	18
Active core equivalent radius/height	46.58 cm / 120 cm
Whole core equivalent radius/height	82 cm / 280 cm
Coolant pressure/speed	20 MPa / 6.92 m/s
Coolant inlet and outlet Temp	655.35 K / 823.15 K
Total mass of Core	39.6 ton

Reflector layer is a 20 cm-thick cylinder of PbO contained within ODS canisters. A 10 cm-thick natural B_4C shield is placed on the outside of the reflector layers. Density of the B_4C shield was 70% of theoretical density.

Table 2 lists design parameters of the KAIST MMR primary control drum (CD) and secondary control rod (CR) systems. The control material was 98% enriched B_4C, with a density about 98% of theoretical density.

Table. 2. Design parameters of Control drum and rod

Item	Control Drum	Control Rod
Material	98% TD, 98 w/o enriched B_4C	98% TD, 98 w/o enriched B_4C
Absorber Geometry	2.5 cm / 120° Thickness / Angle	6.0 cm Radius
Drum Radius	9.5 cm	--
Gap / Cladding thickness	0.1 cm / --	0.1 cm / 0.5 cm

To reduce the initial core excess reactivity, a 0.02 mm-thick burnable absorber (BA) plate is installed in the central assembly duct of the secondary control rod, as shown in Fig. 5. The BA material was 90% enriched boron carbide, with density about 70% of theoretical density. A 0.2 mm-thick ODS steel layer was also coated on the outside of the BA plate in order to mechanically protect it.

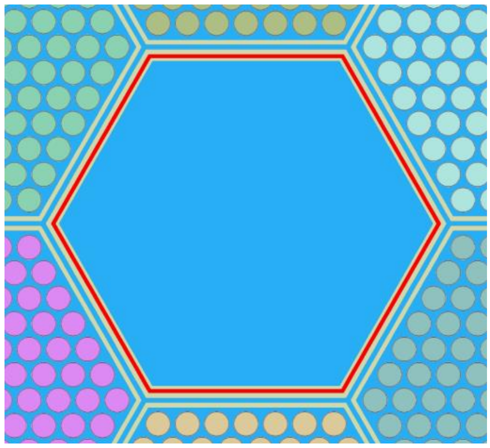


Fig. 5. Burnable Absorber Design

3. Preliminary Neutronics Results

The Monte Carlo depletion analyses were performed with 50,000 neutron histories and 200 cycles in order to properly evaluate the KAIST MMR reactivity depletion, and some safety parameters such as control rod/drum worth, stuck drum worth, Doppler reactivity coefficient and coolant void reactivity (CVR). Temperatures of fuel, cladding and coolant were assumed to be 975 K, 875 K and 750 K, respectively. These values were obtained using a one-dimensional single channel thermal-hydraulics analysis. Nutronics-thermal hydraulic coupling was not considered in this study.

Figure 6 shows depletion of the MMR core with four different $U^{15}N$ enrichments. Average discharged burnup was about 51.6 GWd/MTHM at an average power density of 88.23 W/cc. To achieve reactor lifetime target of 20 EFPYs, relatively high fuel enrichment of

15.5% was utilized since neutron leakage was particularly high due to the small size of the KAIST MMR core. Despite being a fast reactor, its k-eff decreased linearly with burnup since conversion ratio of the core is only between 0.5 ~ 0.6. Initial core excess reactivity is about 4,707 pcm, which should be suppressed near zero during normal operation using the control drums.

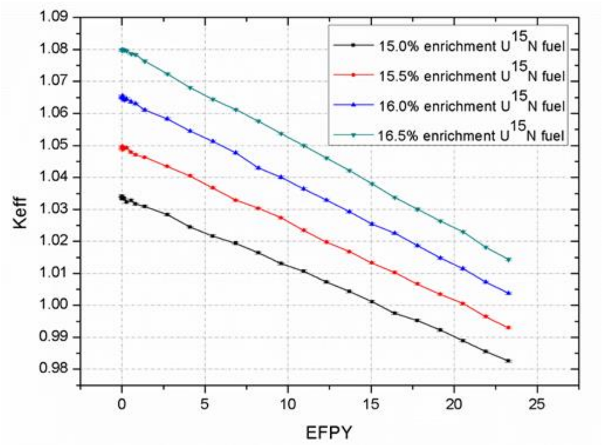


Fig. 6. Depletion results with different enriched $U^{15}N$ fuel

Figure 7 shows the neutron multiplication factor of the KAIST MMR core during a 20-year operation, loaded with 15.5 w/o enriched $U^{15}N$ fuels, with and without BA. With BA, initial reactivity hold-down was about 2,148 pcm. The BA should be removed before the core becomes subcritical. With this BA design, the operating excess reactivity can be reduced and the targeted core lifetime can be achieved quite easily. The period pre-BA removal was termed as 'first half' and post-BA removal 'second half'. It was assumed the reactor was in shutdown mode for about 30 cooling days during the BA removal.

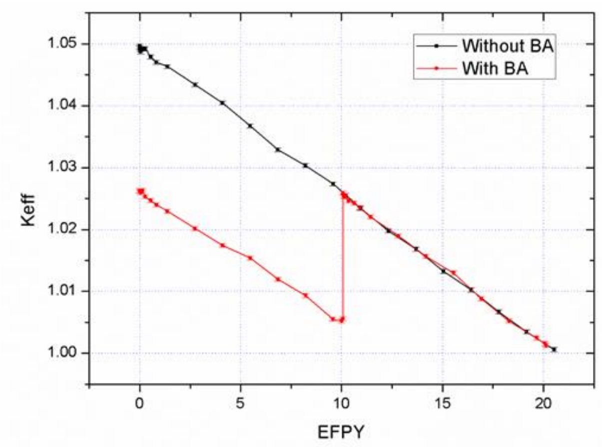


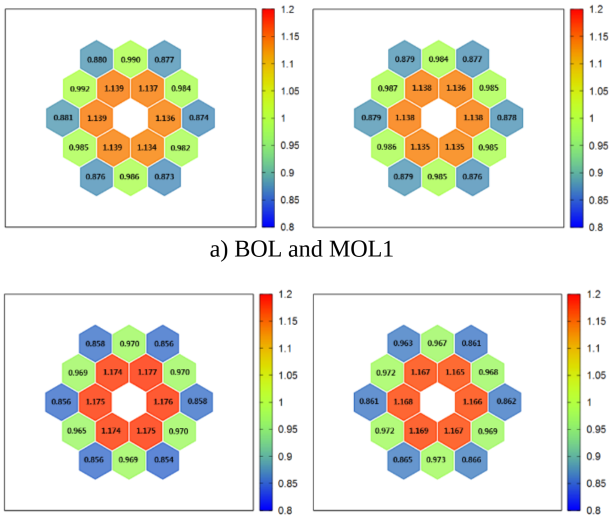
Fig. 7. Depletion results of with and without BA

In the first half, initial reactivity was about 2,559 pcm. The reactivity at MOL1 (middle of life with BA) of the first half was 521.3 pcm. In the second half, initial reactivity at MOL2 (middle of life without BA) was 2,521 pcm, which is similar to that of the first half. Reactivity at EOL of the second half was 159.7 pcm.

Figures 8 and 9 show radial and axial power distributions of the KAIST MMR core. Table 3 tabulates its corresponding power peaking factors. The 3-D power peaking factor, F_q, was evaluated as follows:

$$F_q = PF_{radial} \times PF_{axial} \qquad (1)$$

Maximum spatial power peaking factor of the KAIST MMR is about 1.5.



a) BOL and MOL1

a) MOL2 and EOL

Fig. 8. Normalized Radial Power Distribution

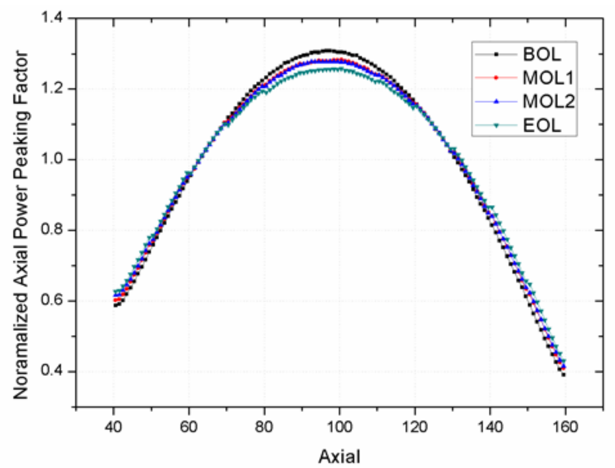


Fig. 9. Normalized Axial Power Distribution

Table. 3 Power Peaking Factor of KAIST MMR

Parameter	First half		Second half	
Peaking Factor	BOL	MOL1	MOL2	EOL
Radial	1.139	1.138	1.177	1.169
Axial	1.308	1.283	1.278	1.258
F_q	1.490	1.461	1.504	1.470

Table 4 lists worth of the primary CD, stuck drum, secondary CR and total rod at All-Rod-In (ARI) condition. Worth of the primary CD and secondary CR are much higher than the initial core excess reactivity of 2,500 pcm. These high worth should provide a sufficient shutdown margin for the core.

Table. 4. Control Rod worth at first half and second half

Parameter		BOL	MOL1
First half	**Primary**	5100.3 ± 46.1	5086.7 ± 48.8
	Stuck	4615.6 ± 45.9	4652.6 ± 47.8
	Secondary	5342.6 ± 46.2	5586.8 ± 50.8
	ARI	11417.5 ± 51.4	11716.4 ± 54.6
Parameter		**MOL2**	**EOL**
Second half	**Primary**	4713.5 ± 46.8	4614.1 ± 51.8
	Stuck	4329.0 ± 46.5	4366.0 ± 49.5
	Secondary	6836.2 ± 47.9	6878.4 ± 53.1
	ARI	12851.0 ± 53.3	12828.2 ± 59.6

*The unit is [pcm]

Table 5 tabulates the Doppler reactivity coefficient and CVR of the KAIST MMR core at BOL, MOL1, MOL2 and EOL conditions. CVRs were calculated by voiding the coolant in the whole core region. All calculated reactivity coefficients are sufficiently negative.

Table. 5. Doppler reactivity coefficient and CVR at first half and second half

Parameter		BOL	MOL1
First half	**Doppler** [pcm/K]	-0.349 ± 0.021	-0.330 ± 0.021
	CVR [pcm]	-350.72 ± 14.16	-33.84 ± 14.07
Parameter		**MOL2**	**EOL**
Second half	**Doppler** [pcm/K]	-0.396 ± 0.020	-0.399 ± 0.018
	CVR [pcm]	-491.98 ± 13.51	-1.47 ± 7.48

4. Conclusions and Future work

In this study, neutronics feasibility of a fully compact and transportable KAIST micro-modular reactor (MMR) was demonstrated. Rated thermal power of the core was 36.2 MWth with total weight of about 39.6 tons. The core was loaded with 15.5 w/o uranium mono-nitride $U^{15}N$ fuels in order to achieve a targeted lifetime of 20 EFPYs.

To achieve targeted lifetime, initial excess reactivity of the core should be quite high, around 4,707 pcm. To reduce the high excess reactivity to about 2,500 pcm, a replaceable burnable absorber was utilized in the design. As a result, the MMR has a 20-year lifetime with a relatively small burnup reactivity swing.

Several important safety parameters of the KAIST MMR core were also determined in this study. The Doppler reactivity coefficients and CVRs were demonstrated to negative. Worth of the primary control drums and secondary control rod were much higher than initial excess reactivity.

In future work, neutronics-thermal hydraulic coupling will be considered and radiation shielding concerns will properly be addressed.

5. References

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