A STUDY OF HANARO CORE CONVERSION USING HIGH DENSITY U-Mo FUEL

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ABSTRACT

Currently, HANARO is using 3.15gU/cc U3Si/Al as a driver fuel. HANARO has seven vertical irradiation holes in the core region. Three of them including a central trap are located in the inner region of the core and mainly being used for material irradiation tests. Four of them are located in the reflector tank but cooled by primary coolant. They are used for fuel irradiation tests or radioisotope development tests. For minimum core modification using high density U-Mo fuels, no dimension change is assumed in the current fuel rods and the cladding thickness remains the same in this study. The high density U-Mo fuel will have up to about twice the linear uranium loading of a current HANARO driver fuel. Using this high density fuel 8 fuel sites can be replaced with irradiation sites. Three kinds of conceptual cores are considered using 5 gU/cc U-7Mo/Al and 16 gU/cc U-7Mo. The increase of the linear heat generation rate due to the decrease of total fuel length can be overcome by more uniform radial and axial power distribution using different uranium densities and different fuel meat diameters are introduced into those cores. The new core has 4.54 times larger surface-to-volume ratio than the reference core. The core uranium loading, linear heat generation rate, excess reactivity, and control rod worth as well as the neutron spectra are analysed for each core.

1. Introduction

Core conversion with higher density fuel allows more flexibility in reactor utilization. There are 23 hexagonal channels and 8 circular channels in the inner core of HANARO. Those 8 circular channels are surrounded by 4 control absorber shrouds and 4 shut-off absorber shrouds. 8 channels located in the outer core are also circular. Currently, 3 hexagonal channels in the inner core and 4 circular channels in the outer core are used as irradiation holes. The objectives of this core conversion study are to increase the number of irradiation sites and also to increase the fuel cycle length by loading more uranium in the core.

In this study, analyses on two kinds of fuel types have been performed; monolithic U-Mo fuel and U-Mo/Al fuel. The current fuel assembly has reduced fuel, whose fuel meat diameter is 14% less compared to the standard fuel, in the outer ring of the hexagonal fuel assembly in order to have more uniform power distribution in the fuel assembly. In this study two different uranium densities are used in a single fuel assembly with two different fuel meat diameters in order to further flatten the power distribution within the fuel assembly. The core characteristics have been analysed for assembly power distribution, core excess reactivity, control rod worth, and neutron spectrum. Those analyses have been performed on the in-pile section of the fuel test loop, and radioisotope production study.

2. Core Configuration and its Characteristics

The reference core is the current HANARO core with 32 fuel assemblies as shown in Fig. 1. The cores under consideration in this study have fresh fuels and simulated with MCNP/4B [1]. The fuel of the reference core is 19.75 w/o U_3Si with the fuel density of 3.15 gU/cc as shown in Table 1. The fuel elements (or rods) with reduced diameter (reduced fuel) are located in the outer ring of the hexagonal fuel assembly which has 36 fuel elements in order to decrease the assembly (or radial) power peaking. The hexagonal fuel assembly has 3 fuel rings while the circular fuel assembly, which consists of 18 fuel elements, has only two fuel rings. In case of LHGR (linear heat generation rate) ratio of the outer to inner ring for the hexagonal fuel assembly, the LHGR of the inner ring is the average of two inner rings. Since the fuel rods at the outer ring in the circular fuel assembly are not reduced fuel but standard fuel, the LHGR ratio for the circular fuel assembly is much higher than that of the hexagonal fuel assembly. Actually, the linear uranium loading (LUL) of the reduced fuel is 74.7% of the standard fuel. LHGR ratio of SOR is showing the difference of this LUL between the standard and reduced

Table 1. Comparison of reference and new core characteristics with fresh fuels at 30 MW

Core No. of fuel assemblies (FA) No. of fuel elements (FE)	Fuel specification (density, diameter and thickness)	Core uranium loading (kg) LUL stand/red (kgU/cm)	LHGR max/avg (kW/m)***	LHGR ratio of outer to inner ring**** (axial peaking)	k_{eff} (CAR at 350 mm) CAR worth (mk)
Reference core 32 FA (20H+12C) 936 FE	U_3Si 3.15gU/cc φ6.35/5.49 mm*	58.92 1.0/0.75	88.2/40.6 110.9/37.1 108.1/54.3 83.3/48.7	1.03 (1.51) 1.17 1.24 1.36	1.17499 110.7
Core A 28 FA (20H+8C) 864 FE	U-9Mo 5.0/4.3 gU/cc* φ6.35/5.49 mm	77.72 1.58/1.02	103.3/45.2 107.2/38.5 106.4/55.3	1.02 (1.53) 0.89 0.95	1.17762 105.0
Core B 28 FA (20H+8C) 864 FE	U-9Mo (5.0/3.7)/(4.3/3.7) gU/cc** φ6.35/5.49 mm	66.96 1.17/0.88	99.9/45.2 102.5/37.8 102.3/55.7	1.07 (1.46) 0.94 0.99	1.16278 109.7
Core C 24 FA (14H+10C) 684 FE	U-7Mo 16.31gU/cc φ6.35/4.8 mm* t0.7/0.6 mm*	77.88 2.02/1.77	147.1/57.9 141.7/47.9 154.4/66.8 108.4/51.8	1.01 0.86 0.92 1.03	1.09619 122.1

*standard/reduced
** upper/lower part of fuel element
*** R: hexagonal fuel assembly (36 rods),
CAR: circular fuel assembly (18 rods) in the control absorber rod (shroud)
SOR: circular fuel assembly (18 rods) in the shut-off rod (shroud)
OR: circular fuel assembly (18 rods) in the outer core

**** Hexagonal fuel assembly has 3 rings. Two inner rings have 6 and 12 fuel rods and an outer ring has 18 fuel rods. Circular fuel assembly has 2 rings. An inner ring has 6 fuel rods and an outer ring has 12 fuel rods.

fuels. Since the OR sites are located in the outer core and have more thermalized neutrons, LHGR ratio of OR is higher than those of CAR or SOR.

Core A has 19.75 w/o U-9Mo with the fuel density of 5.0 gU/cc and 4.3 gU/cc. The 5.0 gU/cc fuels have a diameter of 6.35 mm and are loaded in the inner ring(s) of the fuel assemblies. The 4.3 gU/cc fuels have a diameter of 5.49 mm and are loaded in the outer ring of the fuel assemblies. Now, the reduced fuel has less uranium density as well as smaller fuel meat diameter. Hence, the LUL of the reduced fuel is only 64.3% of the standard fuel. Although the LUL ratio of the reduced to standard fuel becomes less than that of the reference core, the LHGR ratio does not change much since the inner most ring fuels are shielded by the middle ring fuels. When this reduced fuel, however, is introduced into the circular fuel assembly, LHGR ratio is greatly decreased to even less than unity, which means that the LHGR of the inner ring is higher than that of the outer ring. Therefore, even though the number of fuel assemblies are decreased by 4, the maximum LHGR is even decreased from 110.9 kW/m of reference core to 107.2 kW/m of Core A. The LHGR ratio is 0.89 at CAR. If the LUL of reduced fuel is increased, however, in order to decrease the power peaking of CAR fuel or to increase the LHGR ratio of the outer to inner ring toward unity, the peaking factor of the hexagonal fuel assembly will be increased far more than unity. The uranium loading in Core A is 32% more than the reference core but the number of fuel assemblies is less by 4, which means there are 4 more irradiation sites (OR1,2,7 and 8). More analysis on Core A can be found in reference [2].

While Core A is studied for more uniform assembly power distribution in radial direction, Core B is introduced to study the axial power distribution. Axially uniform power distribution contributes not only to the total power peaking but also to the LHGR limit in fuel irradiation tests. As can be seen in Fig. 2, the fuel assembly at R8 in the fresh core of HANARO shows the maximum power between 25 and 30 cm from the fuel bottom and the axial peaking factor is 1.51. This decreases to 1.21 at discharge with 55a/o burnup in cycle 8-1. The ratio of maximum burnup to average is 1.29 between 25 and 30 cm from the fuel bottom. This is mainly due to the flux skewed down by the control absorber rods. In order to decrease the axial peaking factor caused by control rods, 3.7 gU/cc fuel is introduced at lower 45 cm of the fuel rods. The extrusion of different fuel meat diameters in axial direction is not easy and excluded in this study. Axial power peaking factor of R6 near CAR2 is 1.53 in Core A and 1.46 in Core B, showing only 5% reduction. This 5% reduction may not be a trade-off of the 18% less fuel cycle length.

Core C has 16.31 gU/cc fuels with 0.7 mm and 0.6 mm thickness, 6.35 mm and 4.80 mm diameter, respectively. The LUL ratio of reduced to standard fuel in Core C is the same as that in Core A. Core C has 32% more core uranium loading than the reference core even though it has only 24 fuel assemblies. The average LHGR increases as the number of fuel elements decreases from reference core to Core A/B and C. Actually, the number of fuel elements or total fuel length of Core A or B is 92% of the reference core but that of Core C is just 73% of the reference core. The maximum LHGR of the fuel assembly which has more neutronic importance such as R8 and R13 increases relatively more. The thermal margin can be maintained by the increase of surface-to-volume ratio from 6.30 of the standard fuel in the reference core to 28.6 of the standard fuel in the Core C.

3. Utilization Performance

Concerning thermal-to-total flux ratio, the reference core has only two kinds of irradiation sites, while Core C has a variety of choices for irradiation tests as shown in Table 2. According to the limitation on LHGR for the irradiation test, an appropriate irradiation site may be selected without major modification of existing capsules. The characteristics of thermal-to-total flux ratio can be found in the neutron spectra as shown in Fig. 3 which are per lethargy and normalized by the sum. The neutron flux and LHGR at the in-pile section (IPS) of the fuel test loop and the reactivity change due to the IPS are calculated for the reference core and Core C and the results are compared in Table 3. Three pins of 3w/o UO_2 PWR fuels are loaded in the IPS. When the IPS takes up four flow channels (R4,7,8 and IR1) in Core C as shown in Fig. 1, the diameter of the IPS may become 53% larger than that in the reference core where the IPS is installed in IR1 only and can hold more test pins. Basically, since Core C has more uranium but operated at the same reactor power, the neutron flux is about 80% of the reference core. The heating at the outer pressure tube in Core C is also 78.2% of that of the reference core. However, since the IPS in Core C is at IR1 and R4,7, and 8 are loaded with dummy fuels in the simulation, the thermal flux of Core C shows almost the same level with that of the reference core. The reactivity change due to the loading of the IPS in Core C is far less than that of the reference core.

Table 2. Irradiation site characteristics

No. of neighboured FA	Reference core	Core C	Normalized total flux	Thermal-to-total flux ratio
6	CT, IR1&2	R9,16,17	1.0	0.41
5		R10	0.85	0.48
		R4,7,8 & IR1 for	0.68	0.51
4		IPS	0.55	0.58
3		R18		
2	OR3,4,5,6		0.31	0.73
1		OR2,3,5,6,8	0.17	0.79
		OR1		
No. of irradiation sites	7	11 and 4 for IPS		

Table 3. IPS characteristics at IR1 in reference core and Core C

	Reactivity change (mk)	Fast flux at clad max/avg (n/cm^2 s)	Thermal flux in flow tube max/avg (n/cm^2 s)	Heating at outer pressure tube (W/g)
Reference core	-9.9	1.37e14/8.95e13	1.11e14/7.50e13	5.56
Core C	-3.0	1.14e14/6.97e13	1.12e14/7.50e13	4.35

Co-59 is loaded at CT of the reference core and R16 of Core C and the reaction rates at 30 MW are compared as shown in Table 4. The target mixed with aluminium reduces the self-shielding, moderates the neutron effectively, and enhances the cooling with good thermal conduction. The thermal neutrons are 30% of the total neutrons but 90% of reaction rate is by thermal neutron due to its high cross section. There is not much difference in reactivity change

Table 4. Co production characteristics in reference core and Core C

	Location	Reactivity change (mk)	Reaction rate total/thermal (#/cc/s)	Neutron flux total/thermal (n/cm^2 s)
Reference core	CT	-14.9	8.69e12/7.98e12	3.95e14/1.30e14
Core C	R16	-13.2	9.10e12/8.42e12	4.06e14/1.37e14

and reaction rate between reference core and Core C. R16 of Core C has similar level of neutron flux compared with CT of the reference core.

4. Conclusions and Further Study

Applying high density fuel to the existing HANARO core creates more flexibility in neutron utilization. U-Mo fuel of which uranium density is higher than the qualified maximum silicide fuel density of 4.8gU/cc is used such as 5gU/cc U-7Mo/Al and 16.31 gU/cc U-7Mo. Loading higher density fuel allows more irradiation sites by replacing fuel sites but still the core uranium loading can be more, enabling a longer fuel cycle. Reduction of the number of fuel elements causes the increase of the linear heat generation rate but this can be overcome by more uniform power distribution both in the radial and axial direction. Actually, appropriate allocation of linear uranium loading by controlling the uranium density and the fuel meat diameter can even enhance the thermal margin of the fuel. High density fuelled cores are compared with the reference core in utilization performance such as fuel testing and cobalt production. Analyses on core configurations with various fuel geometries remain as a further study.

Acknowledgements
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References

[1] J. F. Briesmeister, MCNP-A General Monte Carlo N-Particle Transport Code, Version 4B, LA-12625-M, March 1997.
[2] K.H. Lee et al, Study on HANARO Core Conversion Using U-Mo Fuel, 6th International Topical Meeting on Research Reactor Fuel Management, March 2002

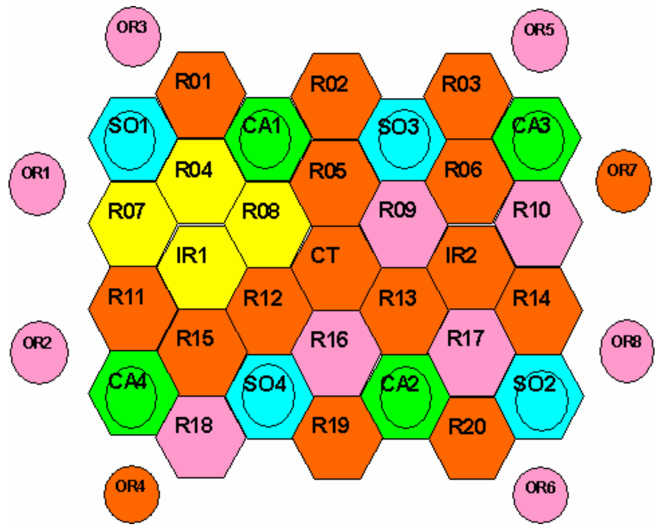

Fig. 1. HANARO core

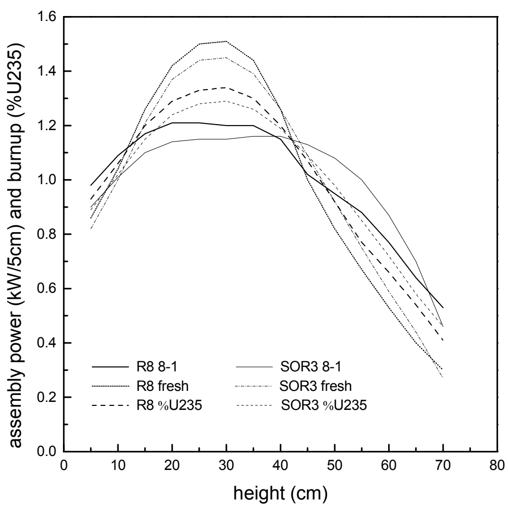

Fig. 2. Axial assembly power and burnup distribution

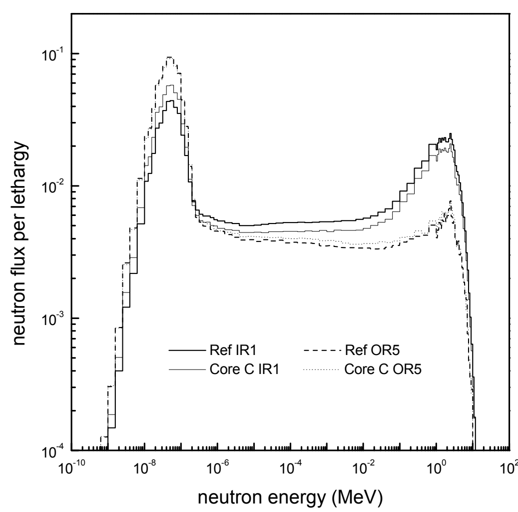

Fig. 3. Neutron spectra at different irradiation sites