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NUCLEAR DESIGN OF KYOTO UNIVERSITY RESEARCH REACTOR (KUR) WITH LEU CORE

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ABSTRACT

Kyoto University Research Reactor (KUR) is a light water moderated / cooled tank-type reactor. The project to convert the KUR fuel from HEU to LEU was achieved and the reactor has been operating since May 28, 2010. The nuclear design of KUR with LEU core is calculated using SRAC code system with JENDL-3.3 and the burnup calculation is performed using SRAC-COREBN. The result of excess reactivity calculation shows good agreement with measurement. In this paper, the nuclear design of KUR is presented and the neutronics characteristics are compared between the LEU core and the HEU core.

1. Introduction

Kyoto University Research Reactor (KUR) is light water moderated / cooled tank-type reactor. KUR attained to first critical at 1964, and since then it is used for many experimental studies on engineering, material science, physics, chemistry, biology and so on. In addition, the neutron beam from KUR core is used for Boron Neutron Capture Therapy in recent years.
The operation of KUR with high enriched uranium (HEU) fuel was ended on February 2006 and the project to convert the KUR fuel from HEU to low enriched uranium (LEU) fuel was achieved in this year. KUR with LEU core has been operating since May 28, 2010.
In this paper, the nuclear design of KUR LEU core is presented and the neutronics characteristics are compared between LEU core and HEU core.

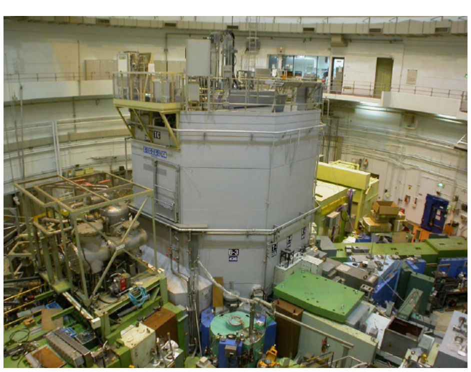

Fig.1 KUR reactor room

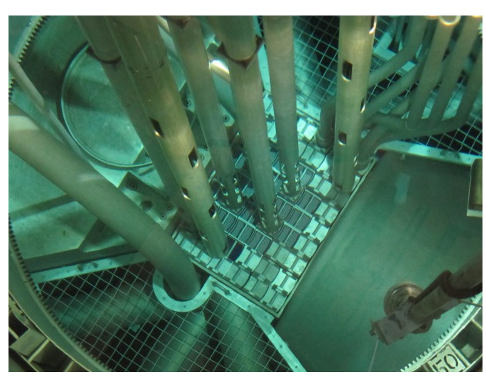

Fig.2 KUR core

3 Specification of KUR LEU fuel

The KUR LEU fuel is an MTR type fuel. The geometrical configuration of LEU fuel is same as HEU fuel. In KUR core, the two types of fuel element are loaded. The one is a standard fuel element and the other is a special fuel element in which the control rod is inserted. The standard fuel element consists of 18 fuel plates and the special fuel element and the special fuel element has 9 fuel plates (see Fig. 3 and 4). The fuel plate consists of 0.5mm-thick fuel meat covered with aluminum cladding of 0.51mm thickness. Thus, the thickness of fuel plate is about 1.5mm. On the other hand, the water gap between the fuel plates is about 2.8mm. Table 1 shows the comparison of LEU fuel and HEU fuel. The 235U enrichment of LEU fuel is 20wt% and the uranium density is 3.2gU/cm3, the HEU fuel has 93wt% 235U enrichment and the 0.56gU/cm3 uranium density. The composition of fuel meat in LEU fuel is U3Si2-Al and that of HEU fuel is U-Al.

Fig.3 A standard fuel element (left) and a special fuel element (right)

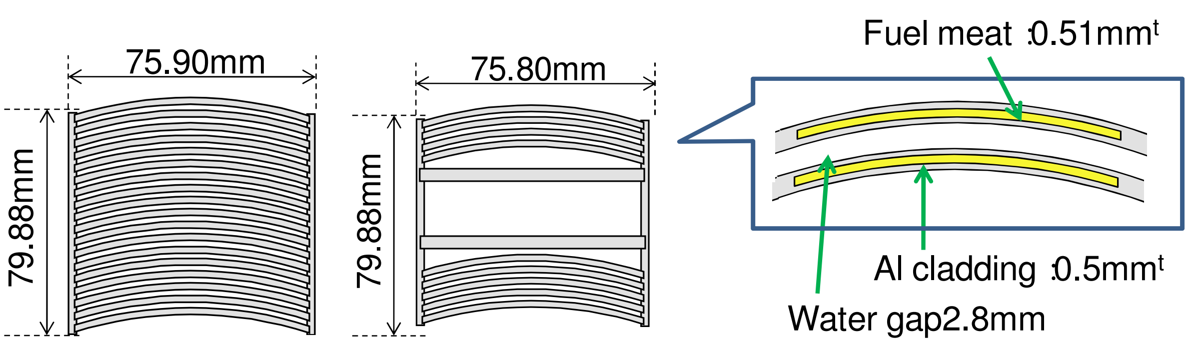

Fig.4 Cross section of fuel element and fuel plate

Table 1 Comparison of LEU fuel and HEU fuel

	235U enrichment	U-density	Composition
LEU	20wt%	3.2gU/cm^3	U_3Si_2-Al
HEU	93wt%	0.58gU/cm^3	U-Al

3. The operation of KUR

The reactor power is changed from 1MW to 5MW in every cycle. After KUR start-up, the 1MW of thermal power is kept for 48 hours and then the power is changed to 5MW. The 5MW operation is continued for 4hours. This operational pattern is defined as 1 cycle operation (see Fig.5).

KUR is operated with 1MW thermal power to carry out experiments and irradiations. In addition, the 5MW operation for 4 hours is conducted for Boron neutron capture therapy (BNCT).

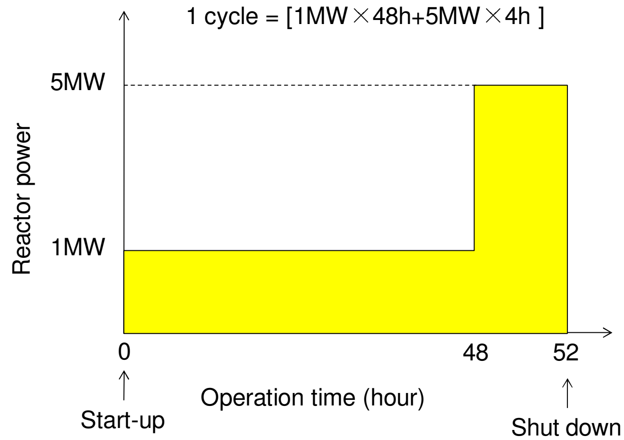

Fig.5 The operating pattern of KUR LEU core

4. Nuclear Design of KUR

4.1 Flow chart of nuclear design calculation

In order to analyze the neutronics characteristics and perform the fuel management, the nuclear design system is newly constructed by SRAC2006 code system [1] and JENDL-3.3 nuclear data library [2]. Figure 6 shows the flow chart of the nuclear design calculation and the calculational condition.

To analyze the neutronics characteristics in KUR core, the 107-gourps cross section set processed by SRAC2006 with JENDL-3.3 was utilized in the cell calculation step. After the processing, the core calculations were performed using SRAC2006/CITATION [1] to evaluate the neutron flux spectrum and the reactivity worth. The Burnup calculations were used by SRAC2006/CORBN [3] code. A three-dimension (X-Y-Z) model was utilized for the core calculations and the burnup calculation.

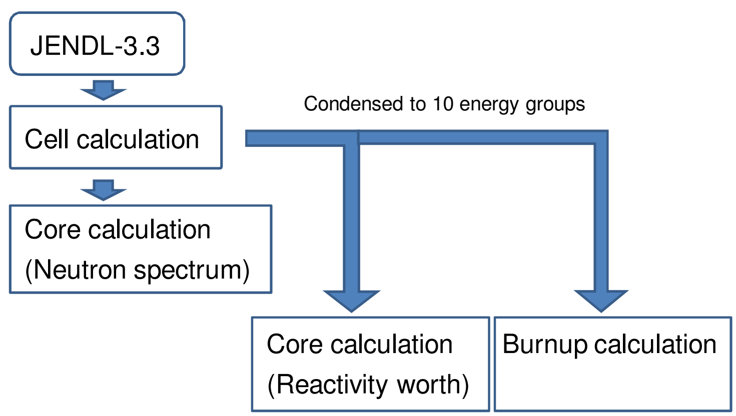

Fig.6 Calculation flow of KUR nuclear design

Table 2 Calculational condition

Calculation step	Code	Energy groups
Cell calculation	SRAC2006 with PEACO routine	107 gr
Core calculation	SRAC2006/CITATION	107 gr
Burnup	SRAC2006/COREBN	10 gr
Reactivity worth	SRAC2006/CITATION	10 gr

4.2 Cell calculation model

In the cell calculation step, the collision probability method with 107 energy groups is used. In resonance energy region, ultra fine lethargy meshes are employed by the PEACO routine [1] in SRAC code. The calculation geometry is a two-dimension (X-Y) model. For example, figure 7 shows the calculational geometry of a standard fuel element. The difference of infinite multiplication factor between the real geometry which is curved fuel plate and the present geometry is about 0.2%dk/k [4].

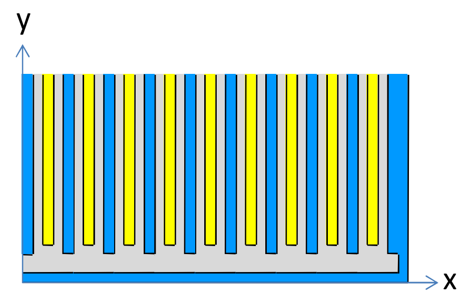

Fig.7 Calculational geometry of a standard fuel element (1/4 geometry)

4.3 Core calculation and burnup model

The core calculations are performed with three-dimension (X-Y-Z) model. . The fuel loading position is shown in Fig.8. This is the initial core configuration with LEU fuel. In the neutron spectrum calculations, 107 energy groups are employed and 10 energy groups are employed for the reactivity worth calculation.

	1	2	3	4	5	6	7	8	9
II	G	R-rod	F	F	F	F	SSS	G	G
RO	G	Pl	F	A-rod	F	B-rod	F	G	Pl
HA	G	Pl	F	F	Hyd	F	F	G	G
NI	G	G	F	C-rod	F	D-rod	F	G	Pn-2
HO	G	G	G	F	F	F	G	G	Pn-3
HE	G	G	G	G	G	G	G	G	Pn-1

Fig.8 Fuel loading position in initial core

F: Standard fuel, G: Graphite reflector, Pl: Water plug
A-D: Special fuel for Shim rods, R: Special fuel for Regulation rod
Hyd, SSS: Irradiation hole, Pn: Pneumatic tube

In the burnup calculation step, the same geometry of core calculation is used. The energy groups are 10 groups. In order to perform the fuel management, the time dependency of 214 nuclides inventory (21 heavy nuclides and 193 F.P nuclides) are evaluated in the burnup model of KUR LEU core.

5. Numerical Results

5.1 Evaluation of neutronics characteristics

In this section, the neutronics characteristics of LEU initial core were evaluated and compared to the case of HEU fuel.
Table 3 shows the comparison of the criticality and the control rod worth. Here, it is assumed that the fuel loading position of HEU core is same position of LEU initial core.
The effective multiplication factor of LEU initial core is 1.0409 and the excess reactivity is 3.93 %dk/k. On the other hand, the case of the HEU fuel has 1.0461 of the multiplication factor and 4.62 %dk/k of the excess reactivity. The ratio of the excess reactivity for the LEU fuel core to that for the HEU fuel core was 0.85. In addition, the control rod worth of LEU core were less than HEU core. The reason is the ^{238}U inventory in LEU fuel is increased remarkably. Therefore the neutron spectrum in the LEU core is harder than the HEU core. However, the remarkable difference of neutronics characteristics between LEU core and HEU core were not observed.
Figure 9 shows the neutron flux spectrum of standard fuel element at position of “HA-4” when the reactor power is 1MW. The thermal flux is deceased about 20% from HEU fuel. The neutron flux spectrum in Hydraulic conveyer (Hyd) is shown in Fig.10. Hyd is an irradiation hole and the position is the center of the core. This figure shows the spectrum of LEU is harder than the HEU fuel.

Table 3 Comparison of the neutronics characteristics between LEU and HEU

		LEU	HEU	LEU/HEU
Effective multiplication factor		1.0409	1.0461	0.995
Excess reactivity (%Δk/k)		3.93	4.62	0.85
Control rod worth (%Δk/k)	A-rod	3.01	3.31	0.91
	B-rod	2.54	2.79	0.91
	C-rod	2.65	2.91	0.91
	D-rod	2.57	2.85	0.90
	R-rod	0.28	0.36	0.78
Max. Reactivity insertion rate ** (%Δk/k/cm/sec)	A-rod	0.0144	0.0187	0.77
	B-rod	0.0114	0.0128	0.89
	C-rod	0.0124	0.0152	0.82
	D-rod	0.0114	0.0129	0.89
	R-rod	0.0067	0.0078	0.86

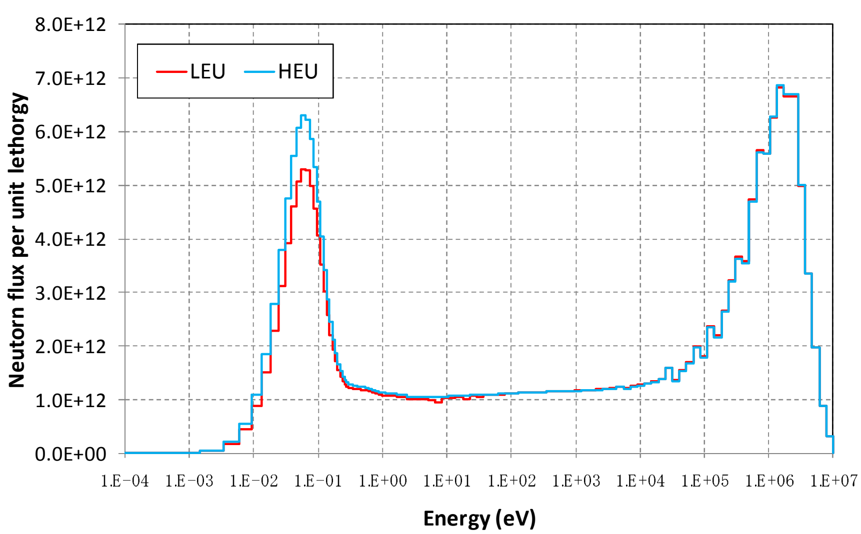

Fig.9 Neutron spectrum in fuel element at the position of “HA-4”

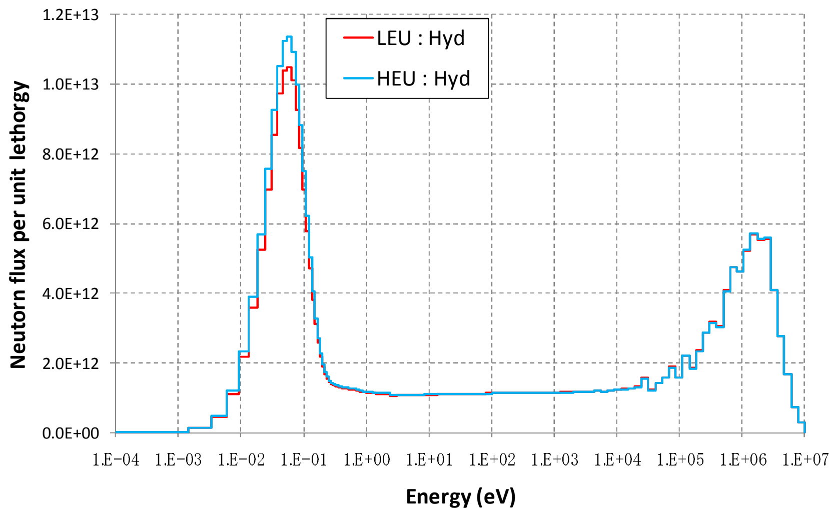

Fig.10 Neutron spectrum in Hyd

The neutron fluxes at the irradiation facility in the core are shown in table 4. The energy regions of fast flux and thermal flux are defined as 10MeV to 0.82MeV and 0.1 eV to 1.0E-5 eV. By converting LEU fuel from HEU fuel, the thermal flux in Hyd reduced about 7.6%. The thermal flux at Pneumatic tube No.1 is about 3.8% smaller than HEU core.

Table 4 Neutron flux at core irradiation facility

Irradiation facility	Energy	LEU (nv/cm^2)	HEU(nv/cm^2)	Difference* (%)
Hyd	Fast	9.04×10^{12}	9.06×10^{12}	-0.22
	Thermal	2.08×10^{13}	2.25×10^{13}	-7.56
Pn-1	Fast	5.22×10^{11}	5.29×10^{11}	-1.32
	Thermal	5.02×10^{12}	5.22×10^{12}	-3.83
Pn-2	Fast	8.96×10^{11}	9.09×10^{11}	-1.43
	Thermal	6.72×10^{12}	7.06×10^{12}	-4.81
Pn-3	Fast	7.09×10^{11}	7.19×10^{11}	-1.39
	Thermal	6.00×10^{12}	6.28×10^{12}	-4.46
SSS	Fast	4.10×10^{12}	4.14×10^{12}	-0.97
	Thermal	5.44×10^{13}	6.04×10^{13}	-9.93

5.2 Comparison of calculation and measurement

At the first, the excess reactivity of LEU initial core was compared between the calculation and the measurement. The excess reactivity was calculated with 107 energy groups. The measurement value was observed by the control rods position in the critical state at zero power operation. The excess reactivity by calculation was 3.93 %dk/k and 3.96%dk/k was the value of measurement. The good agreement was observed.

Table 4 Comparison of excess reactivity

Calculation (%dk/k)	Measurement (%dk/k)	C/E
3.93	3.96	0.99

Figure 11 shows the time dependency of burnup reactivity worth in 1 cycle operation (1MW:48hours+5MW:4hous) of LEU initial core. This reactivity worth were observed by the control rod position during the KUR operating. The buildup of 135Xe concentration mainly contributed to the reactivity worth. Operating with 1MW of reactor power for 45 hours, a reactivity was inserted about -2.2%dk/k into the core. After the 1MW operation, the reactor power was changed to 5MW.

The positive reactivity was inserted into the core because the Xe concentration was reduced by high neutron flux. The reactivity was about -0.5%dk/k. In addition, a negative reactivity was inserted again about 2.5 hours after the power change.
In order to analyze the reactivity worth, the bunup calculation was carried out. The calculated value of the reactivity worth was observed good agreement with the measurement value.

A burnup dependency of the excess reactivity is shown in Fig. 12. The excess reactivity was observed by the critical rod position and that was measured at every reactor start up. The condition of the measurement was low reactor power operation which had no thermal feedback. This figure shows the calculated excess curve is accurate.
Therefore, the nuclear design model of KUR LEU core is reasonable model for fuel management.

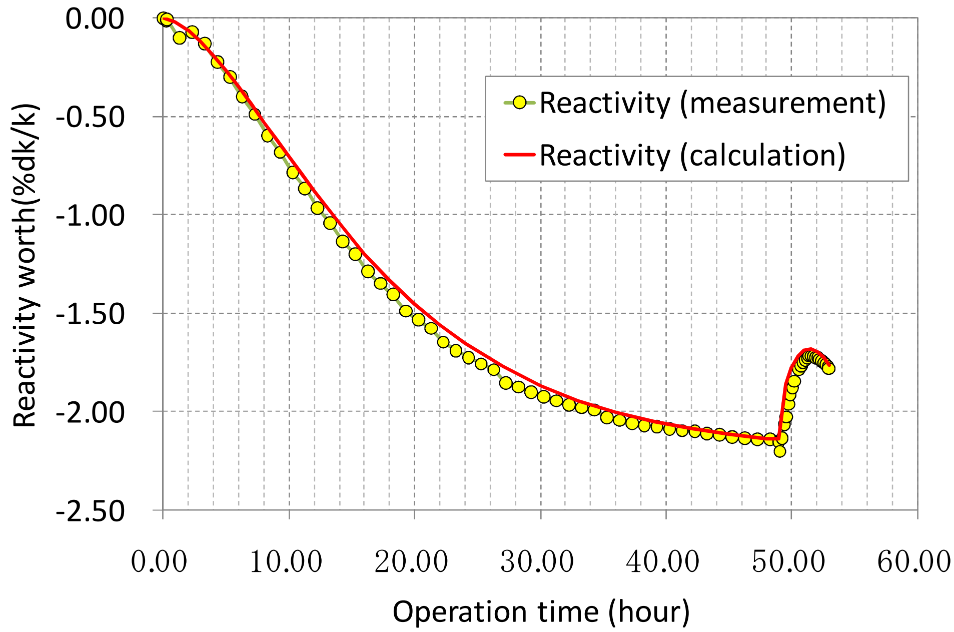

Fig.11 Burnup reactivity worth in 1 cycle operation

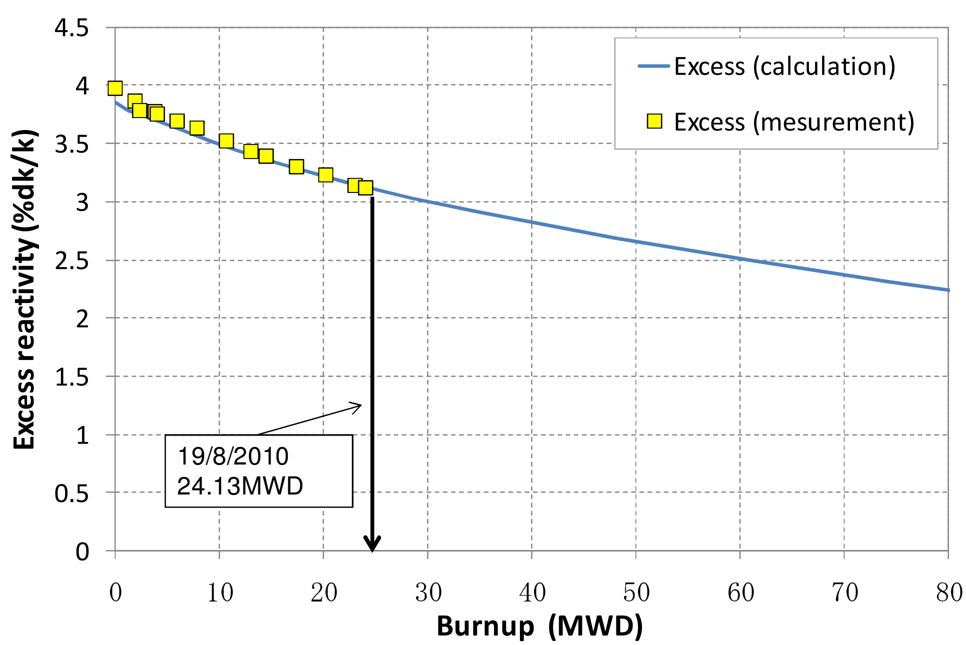

Fig.12 Burnup dependency of excess reactivity

6. Conclusion

In this paper, the new nuclear design system of KUR LEU core was described. The system was constructed by SRAC code system and JENDL-3.3.

The neutronics characteristics of LEU core and HEU core were evaluated by the present system, and the parameters were compared. As the result of analysis, the effective multiplication factor and the control rod worth of LEU core were less than the parameters of HEU core. The reason is the ^{238}U inventory in LEU fuel is increased remarkably. Therefore the neutron spectrum in the LEU core is harder than the HEU core. However, the remarkable difference of neutronics characteristics between LEU core and HEU core were not observed. In addition, it was shown that the thermal neutron flux at the irradiation facility became a decrease in about 7.8% or less.

The calculated excess reactivity of LEU initial core was 3.93 %dk/k and 3.96%dk/k was the value of measurement. The present nuclear design system is possible to analyze the neutronics characteristics of KUR LEU core accurately. In addition, it is described that the calculation value of bunup characteristics were good agreement with the measurement.

A more highly accurate nuclear design system will be improved by acquiring more measurement data, and feeding back to the nuclear design in the future.

References

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