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Analysis of KUCA Type-A Cores

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ABSTRACT

The KUCA experiments on an Accelerator Driven Subcritical Reactor (ADSR) were launched in 2000 at Kyoto University Critical Assembly with the main objective to establish measurement techniques of neutronic parameters in subcritical systems and to investigate the accuracy of the neutronic design of an ADSR. The KUCA ADSR experiments are performed using the solid-moderated and -reflected "type-A" core combined with the pulsed neutron source.

A benchmark model was developed for the analysis of several "type-A" cores combined with a Cockcroft-Walton type accelerator. In these configurations, 14 MeV pulsed neutrons are generated by D-T (deuterium - tritium) reactions and injected through a polyethylene reflector into a subcritical system loaded with polyethylene-moderated highly enriched uranium fuel. This paper shows the results of preliminary calculations that were carried out according to the specifications provided in a KUCA benchmark report. Results of reactivity and indium rate distributions are compared with the measurements. Calculations were also performed to evaluate the conversion of the "type A" cores from high to low enriched uranium. In addition to the reactivity level, the impact on the reactor physics of this conversion was analyzed through the comparison of neutron flux spectra at specific locations.

1. Introduction

The accelerator driven subcritical reactor (ADSR) was developed for energy production and for transmuting minor actinides and long-lived fission products. In recent years, the ADSR has been the object of many studies because of its potential for burning plutonium and nuclear waste, and its intrinsic safety features due to the subcritical state. At the Kyoto University Research Reactor Institute (KURRI), using the Kyoto University Critical Assembly (KUCA) a series of experiments was officially launched in fiscal year 2000 with the purpose of investigating the neutronic features of the ADSR. The KUCA ADSR experiments are performed using the solid-moderated and -reflected "type-A" core combined with the pulsed neutron source. The main objective of these experiments is to investigate typical ADSR neutronic characteristics, such as reaction rate distributions and neutron spectrum, in order to establish measurement techniques of neutronic parameters in subcritical systems and to investigate the accuracy of current ADSR neutronic designs.

A benchmark model [1] was developed for the analysis of several "type-A" cores combined with a Cockcroft-Walton type accelerator. In these configurations, 14 MeV pulsed neutrons are generated by D-T (deuterium - tritium) reactions and injected through a polyethylene reflector into a subcritical system loaded with polyethylene-moderated highly enriched uranium fuel. The present paper shows the results of preliminary calculations that have been carried out according to the specifications provided in the benchmark report [1]. Results of reactivity and indium rate distributions were compared with the measurements. Calculations were also performed to evaluate the conversion of the "type A" cores from high to low enriched uranium. In addition to the reactivity level, the impact on the reactor physics of this conversion was analyzed through the comparison of neutron flux spectra at specific locations.

2. Description of KUCA "Type-A" Cores and Performed Measurements

Following the benchmark specifications, calculations have been performed for the "type-A" core configurations shown in Figures 1 to 8. In these configurations, the core is reflected by polyethylene and the fuel region is obtained by superposition of plates of 93% enriched Uranium-Aluminum (U-Al) alloy and polyethylene. A pulsed neutron generator is combined with the subcritical core for the purpose of injecting 14 MeV pulsed neutrons into the subcritical system through the polyethylene reflector. In some configurations, a neutron shield and the beam duct are installed in the reflector region for directing to the fuel region the high-energy neutrons generated in the tritium target, located outside the polyethylene reflector.

The subcriticality is varied systematically by inserting control or safety rods, or both, into the critical system. For eigenvalue and source calculations, it is required to consider the activation foils set in the position of (15, K) shown e.g. in Figure 6.

An indium (In) wire of 1.5 mm diameter and 60 cm long is set at the core midplane in the axial (vertical) position (16,17–J,W) shown in Figures 1 to 8, for measuring the reaction rate distribution. The experimental results of the In wire are obtained by measuring total counts of the peak energy of γ-rays emitted from ^{115}In(n, n')^{115m}In reactions and normalized by the counts of another irradiated In foil ($20 \times 20 \times 1$ mm^3) in the same location as the tritium target.

Activation foils are also located in relevant positions, including (15, K) and at the tritium target, for measuring the neutron spectrum. In this case, the activation foils are selected to cover a range of threshold energy values as wide as possible for the 14 MeV neutrons. For neutron spectrum

measurements, the activation foils are arranged as an aggregate of several samples, and two of them are irradiated simultaneously at the positions of interest (15, K) and the target, for obtaining neutron spectral information.

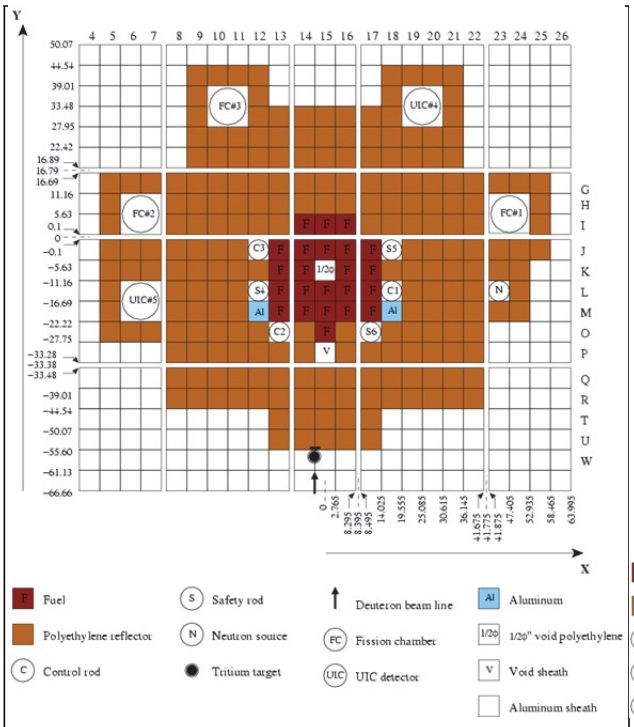

Figure 1. No Neutron Shield and No Beam Duct Core (Series-I: Case I-1)

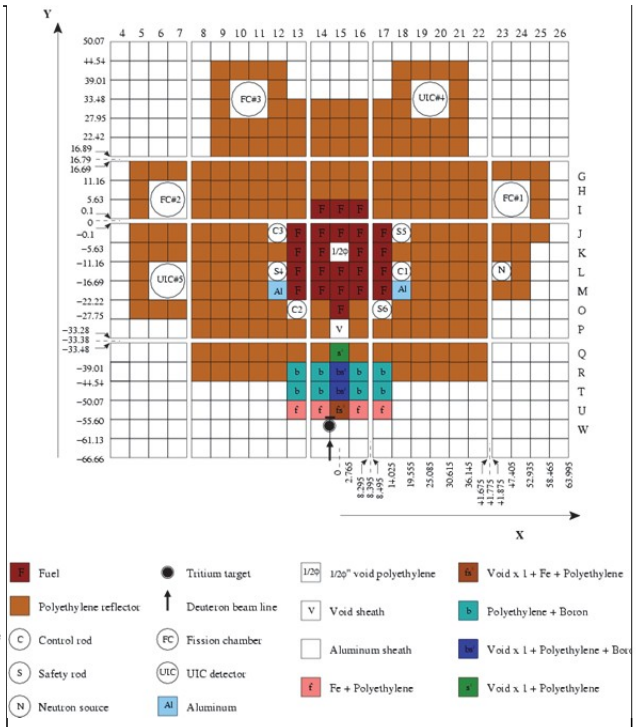

Figure 2. Neutron Shield and Small Beam Duct (s') Core (Series-I: Case I-2)

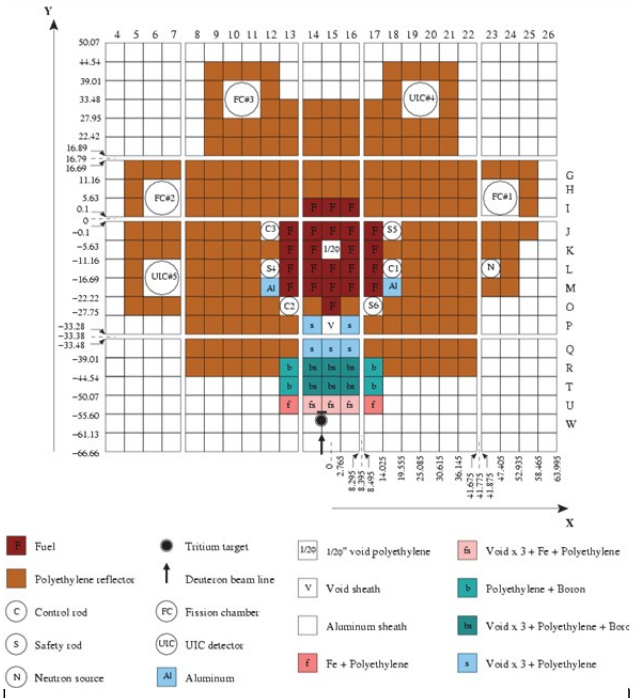

Figure 3. Neutron Shield and Large Beam Duct (s) Core (Series-I: Case I-3)

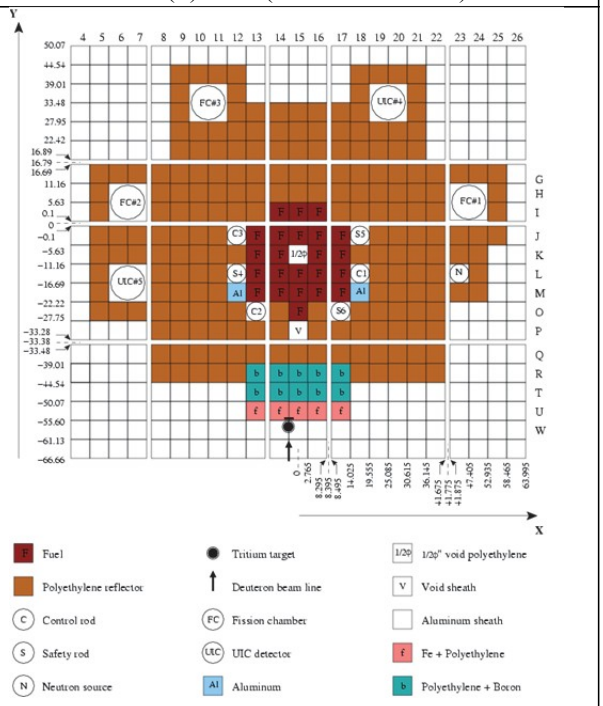

Figure 4. Neutron Shield and No Beam Duct Core (Series-I: Case I-4)

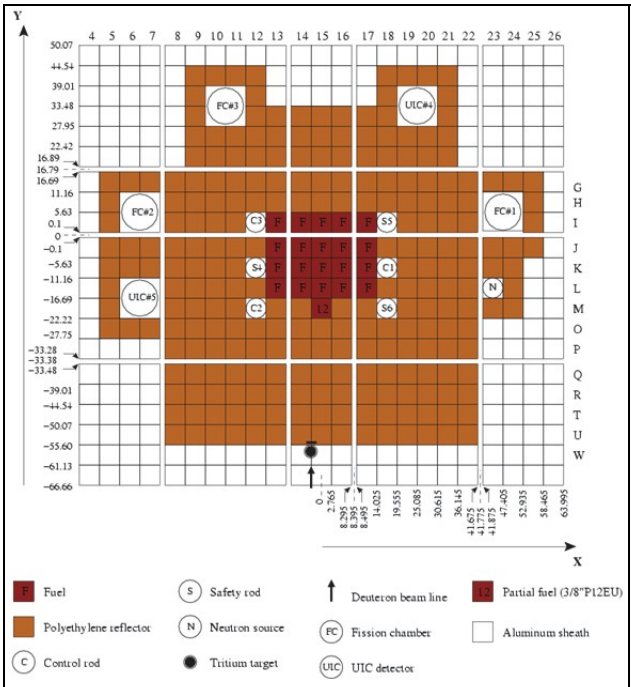

Figure 5. No Neutron Shield, No Beam Duct and No SV Core (Series-II: Case II-1)

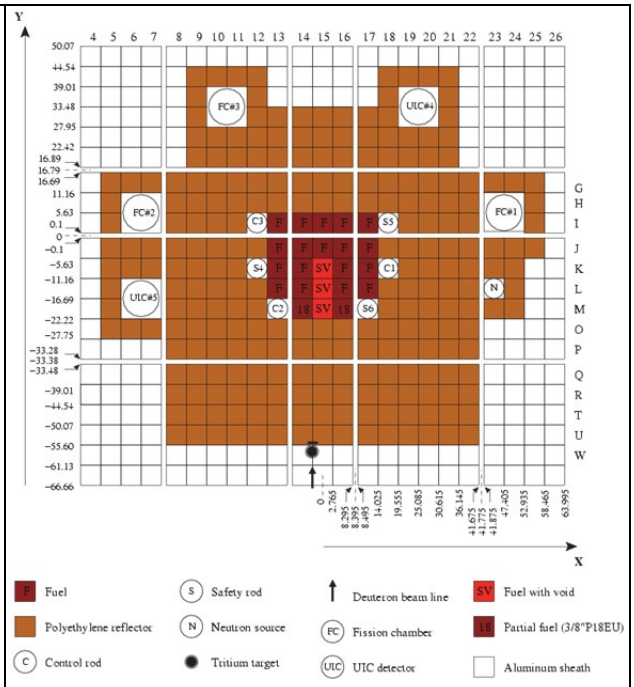

Figure 6. No Neutron Shield, No Beam Duct and SV Core (Series-II: Case II-2)

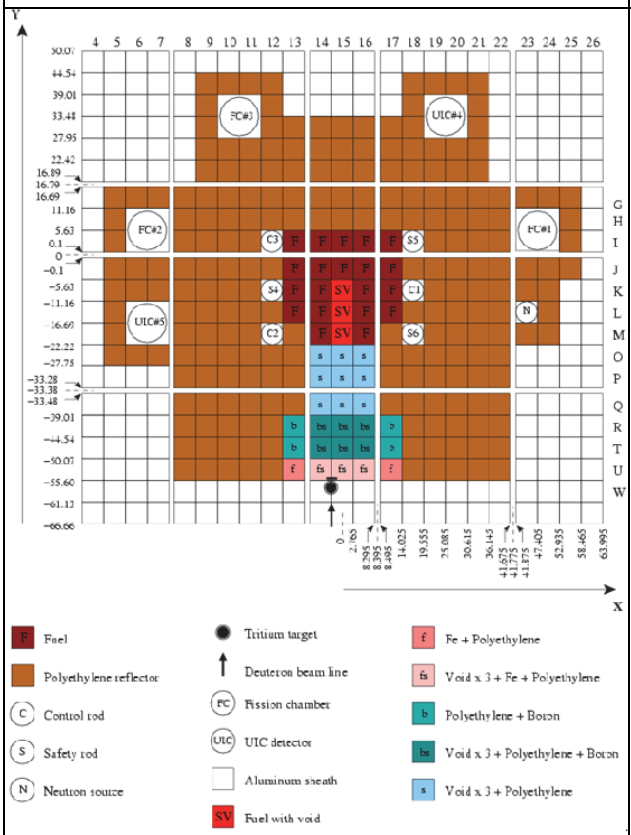

Figure 7. No Neutron Shield, Large Beam Duct (s) and SV Core (Series-II: Case II-3)

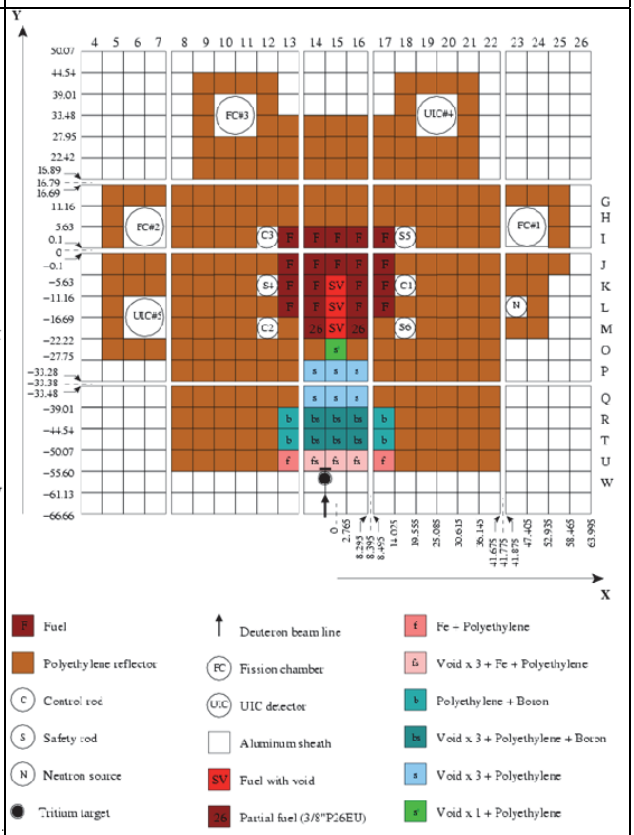

Figure 8. No Neutron Shield, Small Beam Duct (s') and SV Core (Series-II: Case II-4)

3. MCNP Model

Calculations were performed using MCNP Version 5 with ENDF/B-VII.0 cross-section data. Models were developed to accurately represent each component of the fuel, control rods, safety rods and reactor structures.

The materials used in the KUCA assemblies have the form of rectangular parallelepipeds, with a 5-cm^2 (2-in. square) section and thickness ranging between 0.16 and 5 cm. The upper and lower parts of the fuel region are polyethylene reflector blocks more than 50-cm long, as shown in Figure 9. The fuel rods of 93% enriched Uranium-Aluminum (U-Al) alloy consist of 5 × 5 cm^2 cells with 2 polyethylene plates (0.31- and 0.63-cm thick), and a U-Al plate 0.16-cm thick. The core height is approximately 40 cm. The MCNP model was developed by explicitly describing all single plates, both for the polyethylene and the enriched uranium.

For the configurations KUCA II-2, II-3 and II-4 foils have been placed at the location (15,K) as requested in the benchmark specifications. In the absence of additional details on the axial locations, the foils have been placed exactly at the center of the void region of the "SV" assembly as indicated in Figure 10. No foils have been modeled at the location of the tritium target.

The tritium target is located outside the polyethylene reflector. For this reason, the neutron shield and the beam duct were installed in the polyethylene reflector to direct the largest number possible of the high-energy neutrons generated in the target region to the center of the core. For shielding the high-energy and thermal neutrons, the neutron shield consists of several materials: the iron (Fe) for shielding the high-energy neutrons generated in the target region by inelastic scattering reactions and the polyethylene containing 10 wt% of boron for shielding the thermal neutrons, moderated by scattering reactions in the reflector region. For directing the collimated high-energy neutrons to the core region by streaming effect a beam duct of 5 × 5 cm section was created that traverses the reflector and shield assemblies (assemblies bs, bs', fs, fs', s and s' in Figures 1 to 8).

All fuel and reflector/shield rods are inserted in aluminum tubes. The control and safety rods are modeled according to the benchmark specifications and the zero point of the measured rod position was assumed to correspond to the upper surface of the aluminum in the shock absorber, that is 11.4 cm above the fuel assembly base.

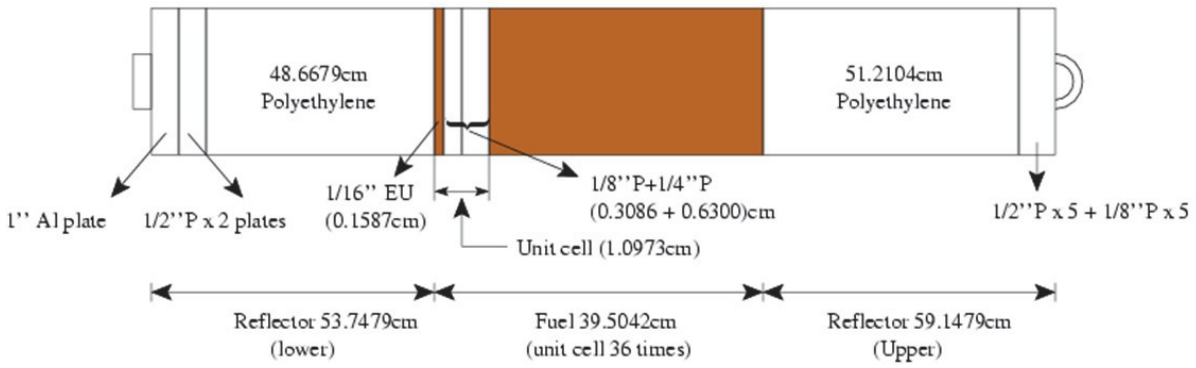

Figure 9. Sideways View of Fuel Assembly "F"

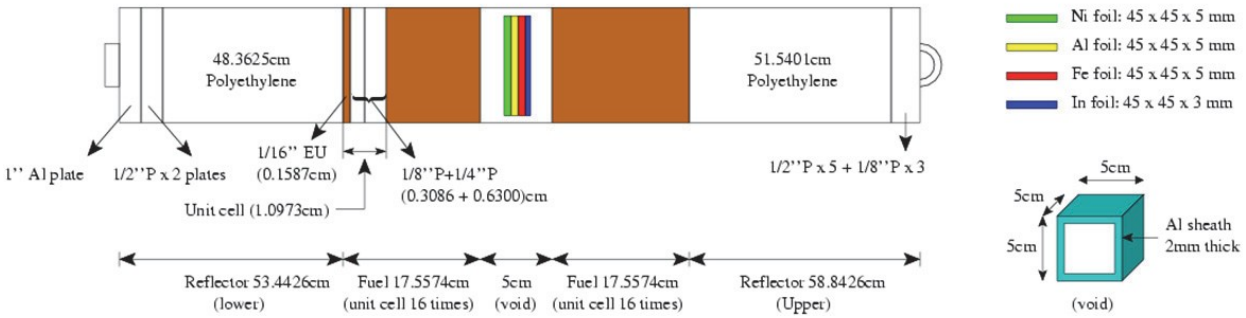

Figure 10. Sideways View of Fuel Assembly "SV" with Foils

4. Reactivity Calculations

According to the benchmark specifications, reactivity calculations were performed with three different control rod configurations:

1. All control and safety rods are fully withdrawn (axial rod position at Z=120 cm). This case provides indication of the excess reactivity of the KUCA reactor configuration.
2. All safety rods are completely withdrawn and control rods C1, C2 and C3 are fully inserted (axial rod position at Z=11.4 cm). This case provides indication of the subcriticality of the KUCA reactor configuration.
3. All safety rods are completely withdrawn and the control rods are at the measured critical position as indicated in Table I for each configuration.

The calculated reactivities are presented in Table II for each configuration together with the experimental values.

Table I. Core Condition, Including Foils, Neutron Shields, SV, In Wire, Partial Fuel and Control Rod Position for the Critical State

Configuration	Foils No.	Partial Fuel	C1 (mm)	C2 (mm)	C3 (mm)	S4-S6 (mm)
KUCA I-1	×		U.L. (*)	U.L.	524.34	U.L.
KUCA I-2	×		U.L.	U.L.	548.21	U.L.
KUCA I-3	×		U.L.	U.L.	745.54	U.L.
KUCA I-4	×		U.L.	U.L.	525.52	U.L.
KUCA II-1	×	12	U.L.	U.L.	635.94	U.L.
KUCA II-2	1	20	637.48	U.L.	U.L.	U.L.
KUCA II-3	1	36	U.L.	U.L.	742.48	U.L.
KUCA II-4	1	26	U.L.	U.L.	553.24	U.L.

(*) U.L.: Upper Limit (1200 mm)

Table II. Calculated and Measured Reactivity (pcm,using ENDF\B-VII.0 Data)

Config.	Rod config.	Experiment	MCNP5	Config.	Rod config.	Experiment	MCNP5
KUCA I-1	Excess React.	+295 ± 21	746 ± 8	KUCA II-1	Excess React.	143 ± 10	776 ± 6
	Subcriticality	-904 ± 63	-371 ± 8		Subcriticality	-793 ± 56	-42 ± 6
	Criticality	0 ±	446 ± 8		Criticality	0 ±	641 ± 6
KUCA I-2	Excess React.	+293 ± 21	695 ± 6	KUCA II-2	Excess React.	246 ± 17	856 ± 6
	Subcriticality	-925 ± 65	-415 ± 6		Subcriticality	-677 ± 47	-18 ± 6
	Criticality	0 ±	422 ± 6		Criticality	0 ±	595 ± 6
KUCA I-3	Excess React.	+20 ± 1	445 ± 6	KUCA II-3	Excess React.	37 ± 3	564 ± 6
	Subcriticality	-1171 ± 82	-616 ± 6		Subcriticality	-893 ± 63	-343 ± 6
	Criticality	0 ±	396 ± 6		Criticality	0 ±	507 ± 6
KUCA I-4	Excess React.	+296 ± 21	746 ± 6	KUCA II-4	Excess React.	232 ± 16	934 ± 6
	Subcriticality	-907 ± 63	-368 ± 6		Subcriticality	-702 ± 49	48 ± 6
	Criticality	0 ±	441 ± 6		Criticality	0 ±	714 ± 6

For all KUCA configurations the calculated reactivity overestimates the experimental values by about 400 to 700 pcm. In an attempt to investigate the observed discrepancy, calculations were also performed with different data libraries. For the KUCA I-1 configuration with all control rods fully withdrawn ("excess reactivity" rod configuration) it was found that the use of JEFF3.1 and ENDF\B-VI.6 data lead to about the same results obtained with the ENDF\B-VII.0 library. Only using ENDF\B-VI.0 data, the obtained reactivity value is ~200 pcm smaller than using the other libraries, reducing the discrepancy with the measured value to ~300 pcm.

For the configurations KUCA II-2, II-3 and II-4, the presence of foils at the center of the void region of the "SV" assembly at the (15,K) location has a reactivity effect of about 800 pcm!

5. Indium Rate Distributions

Indium rate distributions have been calculated along the indium wire in the presence of a (d,t) source. For the simulation, the 14 MeV (d,t) source was uniformly distributed inside a cylinder of 2.25 cm radius and 0.30 cm height, at the location of the tritium target.

The rate distributions were calculated with all control rods C1, C2 and C3 fully inserted (axial rod position at Z=11.4 cm). Unfortunately, for the configuration KUCA II-4 the source calculation was not possible, since with full insertion of the control rods C1, C2 and C3 the model calculates a very slight positive reactivity, which makes the calculated configuration not subcritical.

In order to get a good statistics, up to 600 million histories were needed. Calculation results are presented in Figures 11 and 13, while the measurements are shown in Figures 12 and 14. Note that the axial position Y=0 in Figures 11 to 14 corresponds to Y=-55.6 cm in Figures 1 to 8.

For the Series I configurations and to a lesser extent for the Series II assemblies, the calculated indium rate distributions show a similar "trend" with respect to the measured ones particularly in the fuel zone. In the reflector/shield region the calculations show a depression in the distributions that in some cases is not seen in the measurements that would require further investigations.

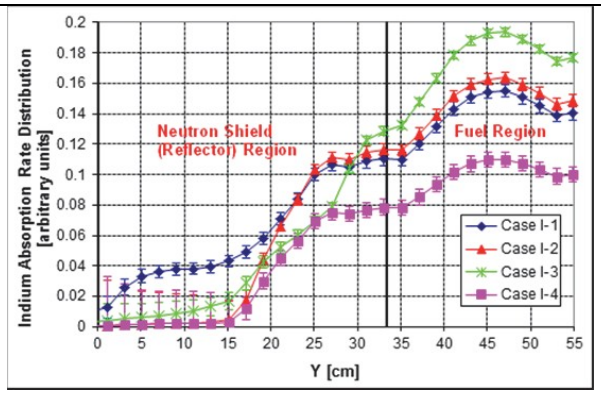

Figure 11. Calculated Indium Absorption Rate Distributions (Case I-1 to Case I-4) in MCNP Units: Rate per One Neutron and One Target Atom $\times 10^{-24}/cm^3$

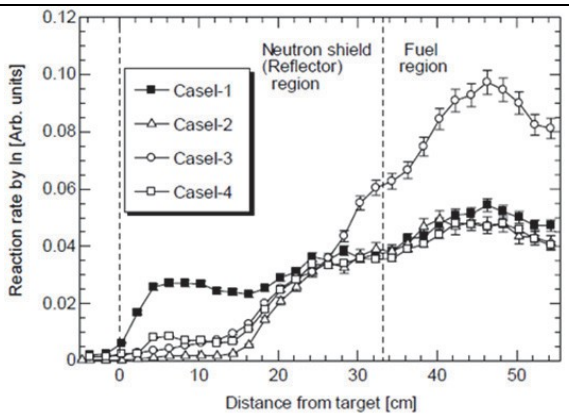

Figure 12. Measured Reaction Rate Distributions by Indium Wire (Case I-1 to Case I-4)

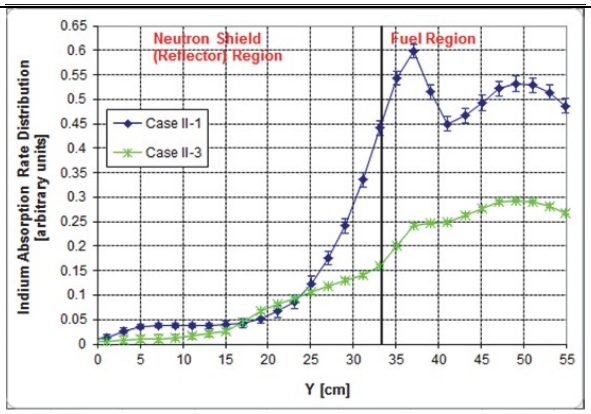

Figure 13. Calculated Indium Absorption Rate Distributions (Case II-1 and Case II-3) in MCNP Units: Rate per One Neutron and One Target Atom $\times 10^{-24}/cm^3$

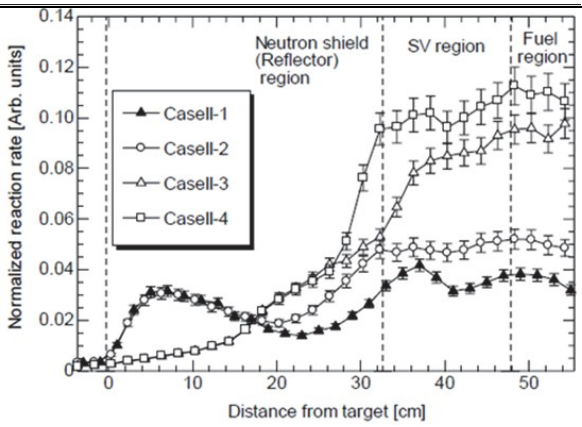

Figure 14. Measured Reaction Rate Distributions by Indium Wire (Case II-1 to Case II-4)

6. Conversion from High to Low Enriched Uranium

Calculations have also been performed to evaluate the spectral and reactivity effects of converting the KUCA series I configurations from high enriched to low enriched uranium (LEU).

If the uranium enrichment is reduced from 93% to 19.75% without changing the fuel composition to high density fuel materials, reasonable values for the multiplication factor are achievable only by increasing the thickness of the fuel plates and the number of fuel assemblies. For the present analysis the fuel plates are always assumed to be made of U-Al alloy, with only the enrichment reduced from 93% to 19.75%. In fact, use of U-9Mo [2] LEU fuel can reduce the required fuel plate inventory and critical core volume, but can also significantly change the core spectrum and other core characteristics. Additionally, for the present study no assumption was made on the constraints related to the inventory of the needed materials.

As an initial attempt to maintain the reactivity of the LEU core, the thickness of the U-Al plates in the fuel assemblies was increased from 0.16 to 0.48 cm. This increase in thickness was

achieved by just replacing the 0.31-cm polyethylene plate of the fuel unit cell by an LEU U-Al plate of the same thickness (see Figure 9). This change results in a reduction of the H/U-235 ratio of the core, leading to a change in the neutron spectrum.

To obtain reasonable k_{eff} values, 56 fuel assemblies had to be added as shown in Figure 15 in the case of the KUCA I-1 configuration. To ensure an efficient reflection, a number of polyethylene assemblies were also added.

For the obtained configurations using LEU, the calculated subcritical levels with all safety rods completely withdrawn and control rods C1, C2 and C3 fully inserted (axial rod position at Z=11.4 cm) and the calculated excess reactivity with all control and safety rods fully withdrawn (axial rod position at Z=120 cm) are presented in Table III.

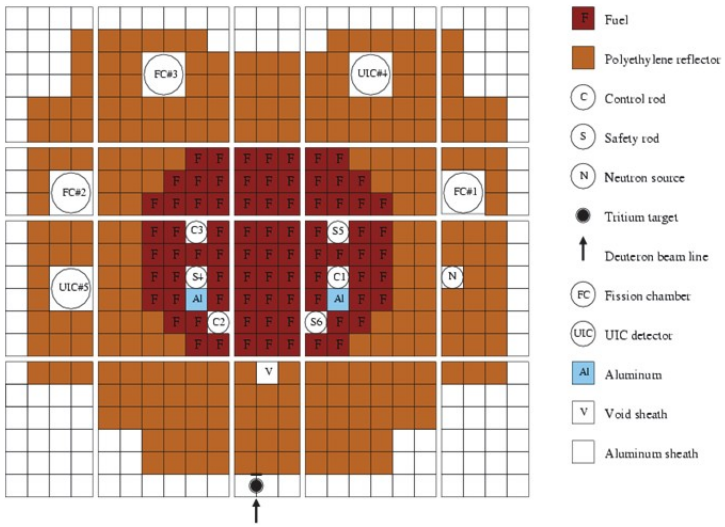

Figure 15. KUCA Configuration Series-I, Case I-1 after Adding 56 Fuel Assemblies

Table III. Calculated Reactivity [pcm] for the LEU Configurations

Configuration	Rod configuration	MCNP5	Configuration	Rod configuration	MCNP5
KUCA I-1	Excess Reactivity	678 ± 6	KUCA I-3	Excess Reactivity	351 ± 5
	Subcriticality	-2857 ± 6		Subcriticality	-3134 ± 6
KUCA I-2	Excess Reactivity	636 ± 5	KUCA I-4	Excess Reactivity	663 ± 6
	Subcriticality	-2891 ± 6		Subcriticality	-2870 ± 6

For the calculated configurations with LEU, flux spectra were calculated at selected positions. Particularly, flux spectra were determined at position A, (X,Y)=(8.395,-2.6) cm, along the indium wire and in position B, in the uranium plate located at the core midplane of the fuel assembly (14,K). The (d,t) source was included in the models.

The flux calculations were performed at the subcritical level characterized by the safety rods completely withdrawn and the control rods C1, C2 and C3 fully inserted (axial rod position at Z=11.4 cm). As shown in Figure 15, the flux energy distributions in the core region show two peaks, one at high energy around 2 MeV and the other at lower energies around 0.1 eV.

Figure 16 shows the comparison of the flux spectra calculated in the same positions B in the high and low enriched uranium configurations. It is observed that using LEU causes the peak at high energy to decrease. This spectrum change is caused by the change in H/U ratio and not due to the use of LEU itself. Generally, the use of LEU should result in hardening of neutron spectrum due to increased absorption by U238.

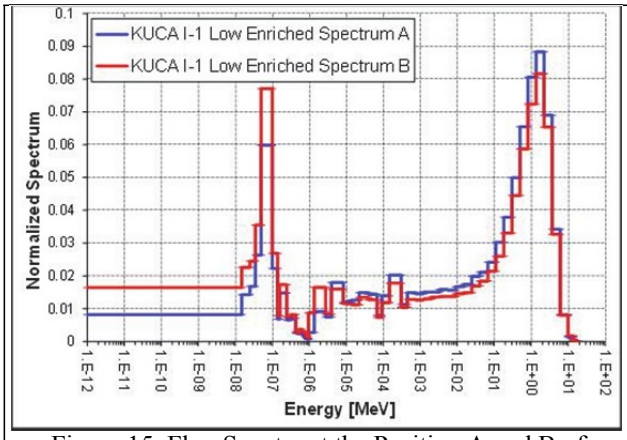

Figure 15. Flux Spectra at the Position A and B of KUCA I-1 with Low Enriched Uranium

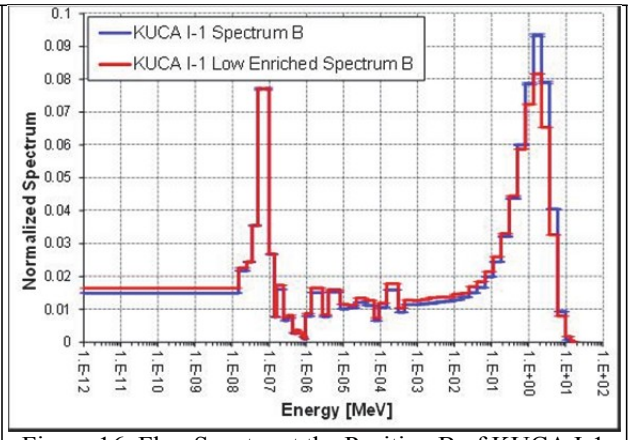

Figure 16. Flux Spectra at the Position B of KUCA I-1 with High and Low Enriched Uranium

7. Conclusions and future work

The KUCA experiments were designed to establish measurement techniques of neutronic parameters in subcritical systems and to investigate the accuracy of the neutronic design of an ADSR. The present report shows the results of preliminary calculations that have been carried out according to the specifications provided in a KURRI benchmark [1]. The calculated results have been also compared with the measurements.

Calculations were performed with MCNP5 and ENDF\B-VII.0 nuclear data. The MCNP model was developed by explicitly describing all single plates, both for the polyethylene and for the enriched uranium.

Based on the benchmark specifications, reactivity calculations were performed with three different control rod configurations. For all KUCA configurations the calculated reactivity overestimates the experimental values by about 400 to 700 pcm. The use of different nuclear data libraries was shown to not have a significant impact on the discrepancies observed between the calculated and experimental results.

Indium rate distributions have been calculated in presence of D-T source along the indium wire located at the core midplane. For the Series I configurations and to a lesser extent for the Series II assemblies, the calculated indium rate distributions show reasonable agreement in the shape of the distribution, particularly in the fuel zone. In the reflector/shield region the calculations show a depression in the distributions that in some cases is not seen in the measurements.

Calculations have also been performed to evaluate the conversion of the KUCA Series I configurations from high enriched to low enriched uranium. No assumption was made on the constraints related to the inventory of the needed materials and the fuel plates were assumed to be made of U-Al alloy. After reducing the uranium enrichment from 93% to 19.75%, reasonable

values for the multiplication factor were achievable only by increasing the thickness of the fuel plates from 0.16 to 0.48 cm and by adding up to 56 fuel assemblies.

For the obtained configurations with LEU, flux spectra were calculated at selected positions. It was found that using LEU the spectrum peak at high energy decreases. This spectrum change is caused by the change in H/U ratio and not due to the use of LEU itself. Generally, the use of LEU should result to hardening of neutron spectrum due to increased absorption by U238. Further calculations are planned to evaluate the use other LEU fuel types in the KUCA assemblies.

8. References

[1] C. Pyeon, "Experimental Benchmarks for Accelerator Driven Subcritical Reactor (ADSR) at Kyoto University Critical Assembly (KUCA)," Kyoto University Research Reactor Institute, Japan, November 2007.

[2] H. Unesaki, T. Misawa, T. Sano and K. Nakajima, "On the Feasibility Study for Utilization of Low Enriched Uranium Fuel at Kyoto University Critical Assembly (KUCA)," RERTR 2011, Santiago (Chile), October 23-27, 2011.